GEORGIA INSTITUTE OF TECHNOLOGY **OFFICE OF CONTRACT ADMINISTRATION**

PROJECT ADMINISTRATION DATA SHEET

[X] ORIGINAL [ ] REVISION NO. ______

Project No. E-16-621 (R5707-2A0) GTRC/~~GIT~~ DATE 1 / 17/ 86

Project Director: B. T. Zinn School/~~Lab~~: AE

Sponsor: Gas Research Institute

Type Agreement: Contract No. 5085-260-1172

Award Period: From 9/1/85 To ~~10~~ 12/31/86 (Performance) 12/31/86 (Reports)

Sponsor Amount:

	This Change	Total to Date
Estimated:	$	$ 52,116
Funded:	$	$ 52,116

Cost Sharing Amount: $ 4,895 Cost Sharing No: E-16-381

Title: Pulsating Burners - Controlling Mechanisms and Performance

ADMINISTRATIVE DATA OCA Contact John B. Schonk x-4820

1) Sponsor Technical Contact:	2) Sponsor Admin/Contractual Matters:
James Kezerle/Robert V. Gemmer	Greg M. Wojciechowski
Gas Research Institute	Gas Research Institute
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Chicago, IL 60631	Chicago, IL 60631
Phone: (312) 399-8100	(312) 399-8177

Defense Priority Rating: N/A Military Security Classification: N/A

(or) Company/Industrial Proprietary: See below

RESTRICTIONS

See Attached N/A Supplemental Information Sheet for Additional Requirements.

Travel: Foreign travel must have prior approval — Contact OCA in each case. Domestic travel requires sponsor approval where total will exceed greater of $500 or 125% of approved proposal budget category.

Equipment: Title vests with Sponsor.

COMMENTS:

See Sections 11 and 12 concerning Patent and Data Rights.

Follow-On to E-16-662

COPIES TO: SPONSOR'S I. D. NO. 02.500.006.85.001

Project Director	Procurement/GTRI Supply Services	GTRC
Research Administrative Network	Research Security Services	Library
Research Property Management	Reports Coordinator (OCA)	Project File
Accounting	Research Communications (2)	Other Jones/ Legal

GEORGIA INSTITUTE OF TECHNOLOGY — OFFICE OF CONTRACT ADMINISTRATION

SPONSORED PROJECT TERMINATION/CLOSEOUT SHEET

Date 6-15-87

Project No. E-16-621 — School/~~Lab~~ AE

Includes Subproject No.(s) N/A

Project Director(s) B.T. Zinn — GTRC / ~~GIT~~

Sponsor Gas Research Institute

Title Pulsating Burners - Controlling Mechanisms and Performance

Effective Completion Date: 12/31/86 (Performance) 4/30/87 (Reports)

Grant/Contract Closeout Actions Remaining:

- [ ] None
- [X] Final Invoice or ~~Final Fiscal Report~~
- [ ] Closing Documents
- [X] Final Report of Inventions - Questionnaire to P.I.
- [ ] Govt. Property Inventory & Related Certificate
- [ ] Classified Material Certificate
- [ ] Other ______

Continues Project No. ______ Continued by Project No. ______

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Other Duane H.
Angela DuBose
Russ Embry

FORM OCA 69.285

CATALYTIC PULSE COMBUSTION

First Semi Annual Report
October 1985 - March 1986

Prepared by

B. T. Zinn, B. R. Daniel and R. Gal-Ed

School of Aerospace Engineering
Georgia Institute of Technology
Atlanta, GA 30332

Gas Research Institute
Contract No. 5085-260-1172

GRI Project Managers
James A. Kezerle
Robert V. Gemmer

April 1, 1986

RESEARCH SUMMARY

Title	Catalytic Pulse Combustion
Contractor	Georgia Tech Research Institute
Contract Number	GRI Contract 5085-260-1172
Report Period	October 1985 to March 1986 First Semi-Annual Report
Principal Investigator	B. T. Zinn and B. R. Daniel
Objectives	The objective of this study is to investigate whether the performance of catalytic combustors can be improved by operating them under pulsating flow conditions.
Technical Perspective	Catalytic combustion processes involve both heterogeneous surface reactions and homogeneous gas phase reactions. At low temperatures (i.e., $T < 1000^{o}K$) the gas phase reaction rate is negligible and the combustion occurs primarily at the catalyst surface. If the combustible mixture enters the catalyst section at a temperature that is considerably above the "light on" temperature ($T > 800^{o}K$), the diffusion processes of reactants and combustion products between the surface and the gas bulk are rate controlling. However, based upon earlier mass transfer studies in oscillating environments, it is expected that operating the catalytic combustor under pulsating conditions will enhance mass transfer rates to and

from the catalyst surface and thus increase the apparent surface reaction rate.

As flow proceeds along the catalyst, the bulk gas temperature increases due to heat transfer from the catalyst surface. This, in turn, promotes gas phase reactions at the downstream section of the catalyst. If the catalyst is operated under pulsating conditions, the pulsations are expected to enhance heat transfer from the catalyst walls to the gas phase thus shortening the induction length of the gas phase reactions.

It is, thus, expected that operating the catalytic combustor under pulsating conditions will increase the output of the catalytic combustor, and/or decrease the amount of catalyst and size of combustion needed for a certain reactant flow rate.

Technical Approach

In the first phase of this study an experimental setup is being developed which will be used to investigate the dependence of a catalytic combustor performance upon the fuel/air ratio, the mixture flow rate, the mixture inlet temperature, the pulsation's frequency and amplitude, and the location of the catalyst section on the standing acoustic wave. Methane/air mixtures will be investigated and the catalyst performance will be determined from temperature and exhaust gas composition measurements. The effect of pulsations will be determined by comparing the combustor performance under steady and pulsating operating conditions.

Program Plan The program is divided into two major tasks which are briefly described below:

Task I - Development of the Experimental Setup.

A Determination of range of investigated test conditions and measurements to be performed.

B Design of the experimental setup.

C Fabrication of the experimental system.

D Assembly and checkout of the experimental setup.

Task II - Test Program:

A Determine the steady state combustion characteristics of the developed catalytic combustor.

B Investigate the dependence of the catalytic combustor performance upon the amplitudes and frequencies of the pulsations when burning lean mixtures and the catalyst is located at a pressure node.

C Investigate the dependence of the catalyst performance upon its location within the acoustic field.

D Investigate the dependence of the pulsating catalytic combustor performance upon mixture composition and its initial temperature.

Results

During the period 10/1/85 to 3/31/86 the proposed experimental setup was designed, most system components were purchased and/or fabricated and the system assembly has been nearly completed.

INTRODUCTION

Catalytic combustors offer specific advantages for a variety of applications. For example, the lower temperature of their exhaust gases makes them suitable for gas turbines; the low levels of concentration in their exhaust products makes them attractive from an environmental point of view; and their ability to burn extremely lean fuel/air mixtures enables them to recover energy which otherwise would be wasted.

Under many operational conditions, the output of catalytic combustors is limited by the rate of diffusion of the reactants and products to and from the catalysts surface, respectively. The chemical reactions in the upstream section of the catalytic combustor occur mostly on its surface. The heat released on the catalyst surface is transferred, however, to the flowing gas stream at some downstream station. The resulting heating of the gas phase leads to the occurrence of homogeneous gas phase reactions in the downstream section of the catalytic combustor. The location where these gas phase reactions are initiated depends upon the rate of heat transfer from the catalyst surface and the gas phase. Consequently, to increase the output of catalytic combustion one have to find means for increasing the rate of mass and heat transfer to and from the catalyst. In related studies, it has been shown that both heat and mass transfer processes are enhanced when they occur in an acoustic field. In view of these observations, the present study will investigate whether the performance of catalytic combustors can be improved by operating them under pulsating conditions. More specifically, this study will investigate the ranges of amplitudes and frequencies which optimize the operations of catalytic combustors.

OBJECTIVES

The objective of this research program is to determine whether the performance of catalytic combustors burning lean methane/air mixtures can be improved by operating them under pulsating conditions. The extent of the resulting improvements will be determined by comparing the performance of the investigated catalytic combustor when operating under pulsating and steady state conditions. Furthermore, the dependence of the combustor performance upon the amplitude and frequency of pulsations, at the location of the catalyst within the acoustic field will be investigated.

TECHNICAL PROGRESS

Work performed during the reporting period (October 1985 - March 1986) concentrated on completing the efforts proposed under Task I. A large fraction of this work has been completed to date as described in the following sections.

A - Determination of Ranges of Experimental Conditions to be Investigated and Measurements to be Performed.

A.1 Catalyst: The investigated catalytic combustor will consist of up to 4 catalytic monolith segments having identical properties. At this point, all tests will be conducted with these 4 catalyst segments and the number of these segments will not be used as an investigated parameters. The investigation will be conducted with lean methane/air mixtures to avoid poisoning of the catalyst with carbon deposits.

A.2- Combustor Diameter: A 2.5 inch inside diameter catalytic combustor will be investigated in this study. The chosen catalyst diameter was a compromise between the need to minimize both wall heat losses and cost of operation. Safety considerations have also entered into this decision. The above decisions was also influenced by our discussions with Dr. Kesserling from the Alzeta Corporation who reported that they had experienced difficulties in accuracy of measurements when they utilized catalysts of diameters smaller than two inches.

A.3- Control of Flow Velocities:Rotameters on both the air and methane lines will be used to control the flow velocities in the range from zero up to 30m/sec in the combustor.

A.4- Combustor Inlet Temperature: Four electric heaters with total output of up to 12 KW will control the temperature of the mixture entering the catalytic combustor. A variable voltage regulator will be used to control the operation of the various heating elements and the system is expected to provide capabilities for heating the incoming gas mixtures to any desirable temperature up to 600 C.

A.5- Acoustic Pressure Measurements: The characteristics of the excited acoustic field will be determined by the use of up to 10 piezo-electric pressure transducers. To avoid heat damage to these transducers, they will be attached to "semi infinite tubes" at a location of approximately 20 inches from the catalytic reactor surface. The "semi infinite tubes" technique will be used in these measurements to eliminate the dependence of the measured data upon frequency.

A.6- Temperature Measurements: Desired temperatures will be measured by use of chromel-alumel thermocouples capable of measuring temperatures up to 1350°C. Capabilities for up to 12 simultaneous temperature measurements will be provided. Both axial and radial temperature distributions within the catalytic combustor will be determined.

A.7- Location of the Catalytic Combustor: During the initial phase of this study the catalytic combustor will be located at an acoustic pressure mode (i.e., a velocity antinode). Provisions have been made, however, which will allow moving the catalytic combustor section to any location on the standing acoustic wave.

Initially, the desired acoustic pulsations will be excited by use of two acoustic drivers with a total power output of up to 100W. However, if the need arises, this system could be upgraded by the addition of two additional acoustic drivers with a resulting total power output of 300W. These acoustic drivers can excite standing acoustic waves in the experimental setup in the frequency range of 200 to 1500 Hz. Higher acoustic power output can be obtained, if needed, by use of available electro pneumatic acoustic drivers.

B - Design of Experimental Setup:

B.1- Description of the Experimental Setup: Drawings of the experimental set up are provided in the Appendix. It consists of a vertical pipe which connects to a horizontal pipe. Air will be supplied through the vertical section where the air heaters are located. Fuel will be injected into the air stream as it enters the horizontal section. After passing through a mixing section, the methane/air mixture will enter the catalytic combustor section. The combustion products will leave the system through a downstream exhaust pipe. Two or four acoustic drivers will be attached to the horizontal pipe walls just upstream of the exit plane. The horizontal pipe section, which contains the catalytic combustor, consists of a number of interchangeable pipe sections. These pipe sections will be moved around whenever the need will arise to position the catalytic combustor at a specific location on the standing acoustic wave.

The developed experimental setup will be mounted on a support system consisting of metal-lumber sections. This structure will be mounted on four casters which will make the whole experimental setup mobile.

B.2- Air Line: The combustion air will be supplied by a compressed air line. Prior to entering the combustor, the air will pass through a filter system which will remove any particulates, condensed moisture and oil mist from the line. The air pressure will be controlled by a pressure regulator. A flexible hose will connect the air line to a rotameter which will be mounted on the mobile structure. From the rotameter the air will move through a pressure valve into the inlet section of the experimental setup.

B.3- Methane Supply: The needed methane will be supplied by a methane bottle, via a pressure regulator, to a methane rotameter. From the rotameter the methane will move through a line which will include a normally closed solenoid valve and a flame arrestor to the methane injector.

B.4- Electrical Hookup: A 220 volt 60 amp line will supply electricity to the air heaters. It will be controlled by a switching system and a variable voltage regulator.

A 115 amp line will supply the power needed to operate the acoustic drivers. In addition, this line will be used to operate the solinoid shutoff valve in the methane line and supply the power required for any of the utilized instruments.

B.5- Exhaust System: The exhaust system will consist of 8 inch circular duct which will be connected to an exhaust fan. The exhaust fan will have a large capacity as it will have to move both the combustion products generated in the catalytic combustor and the additional air with which it will be mixed in order to reduce the flow temperature to below 400^{o}C before leaving the building.

B.6- Data Acquisition System: A 32 channel data acquisition system will be utilized to acquire the data measured during the proposed experiments. This system will utilize an IBM AT Computer and it will be capable of handling the 10 simultaneous acoustic pressure measurements and the 12 simultaneous temperature measurements.

B.7- Composition measurements: A previously developed gas composition analysis system capable of measuring the concentrations of CO, CO_2, NO_x, SO_2, O_2 and hydrocarbons is available in the combustion laboratory and will be utilized in the course of this research program. Specifically, this system will be utilized to determine the composition of the products generated in the catalytic combustor and this data will be used to determine the combustor's combustion efficiency.

C. - Status of Experiment:

All the materials required for the development of the experimental setup have been purchased and fabrication of all components has been completed in the AE department workshop. Furthermore, assembling of the experimental setup is near completion and checkout experiments are planned for the very near future.

PLANNED WORK

The assemblying of the experimental setup will be completed in the very near future. Remaining tasks include: assembly of the electric heaters, the catalytic combustor section and the methane line.

Checkout tests will begin towards the end of April and continue through May. Task II will begin in June and will initially concentrate on determining the steady state performance of the catalytic combustor.

APPENDIX

Drawings of the pulse catalytic combustor to be investigated under this program.

	—	REUVEN	K. Bar-Eli		
MATERIAL	NO. REQD.	DRAWN BY	APPROVED BY	ENG. CHK. BY	PROJECT
SCALE 1:8	Catalytio Pulsed Combustor:				Drawing №
DATE 12-6-85	Assembly Drawing				E-16-621-01

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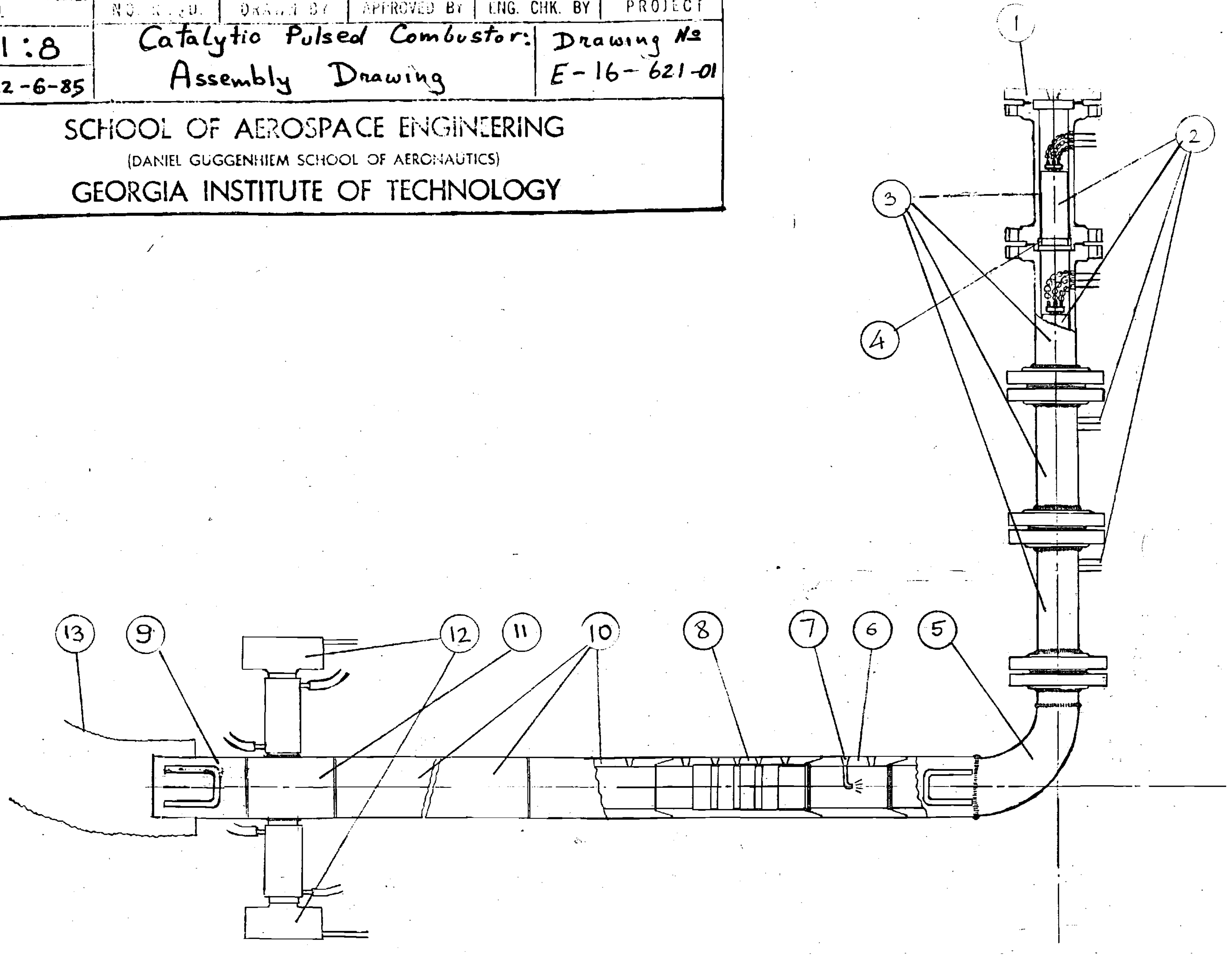
GEORGIA INSTITUTE OF TECHNOLOGY



Part №	Quantity	Description	Remarks
13		Aluminum duct (radial)	8" duct Connected to blower
12	2 or 4	Acoustic drivers – electrical	University Sound model ID-75 - 8 ohm
11.	1	Acoustic drivers' coupler & Coders	Drawings Nos E-16-621-50/53/56 & 58
10	7×1	Variable Acoustic tube sections	Drawing № E-16-621-49
9	1	Exhaust Pipe	Drawings Nos E-16-621-27/22 & 29
8	1	Catalyst Section	Drawings Nos E-16-621-40/42 & 44
7	1	Methane inlet	Through 1/4 stainless tube with flame arresto
6	1	Methane injection Section	Drawings Nos E-16-621-30 & 33
5	1	Hot air inlet	Drawings Nos. E-16-621-20/22 & 23
4	4	Stop for heater (in holder)	Drawing №. E-16-621-11
3	4	Heater holder	Drawing №. E-16-621-10
2	4	Electric air heater	220V 1200/1800 w, Leister model 37 E
1	1	Air inlet flange	2"-150 lb blind flange with 3/4" NPT thread

		REUVEN	R. GAL-ED		E-16-621
MATERIAL	NO. REQD.	DRAWN BY	APPROVED BY	ENG. CHK. BY	PROJECT
SCALE		Catalytic Pulsed Combustor:			Drawing №
DATE	12-30-85	Parts' List			E-16-621-03

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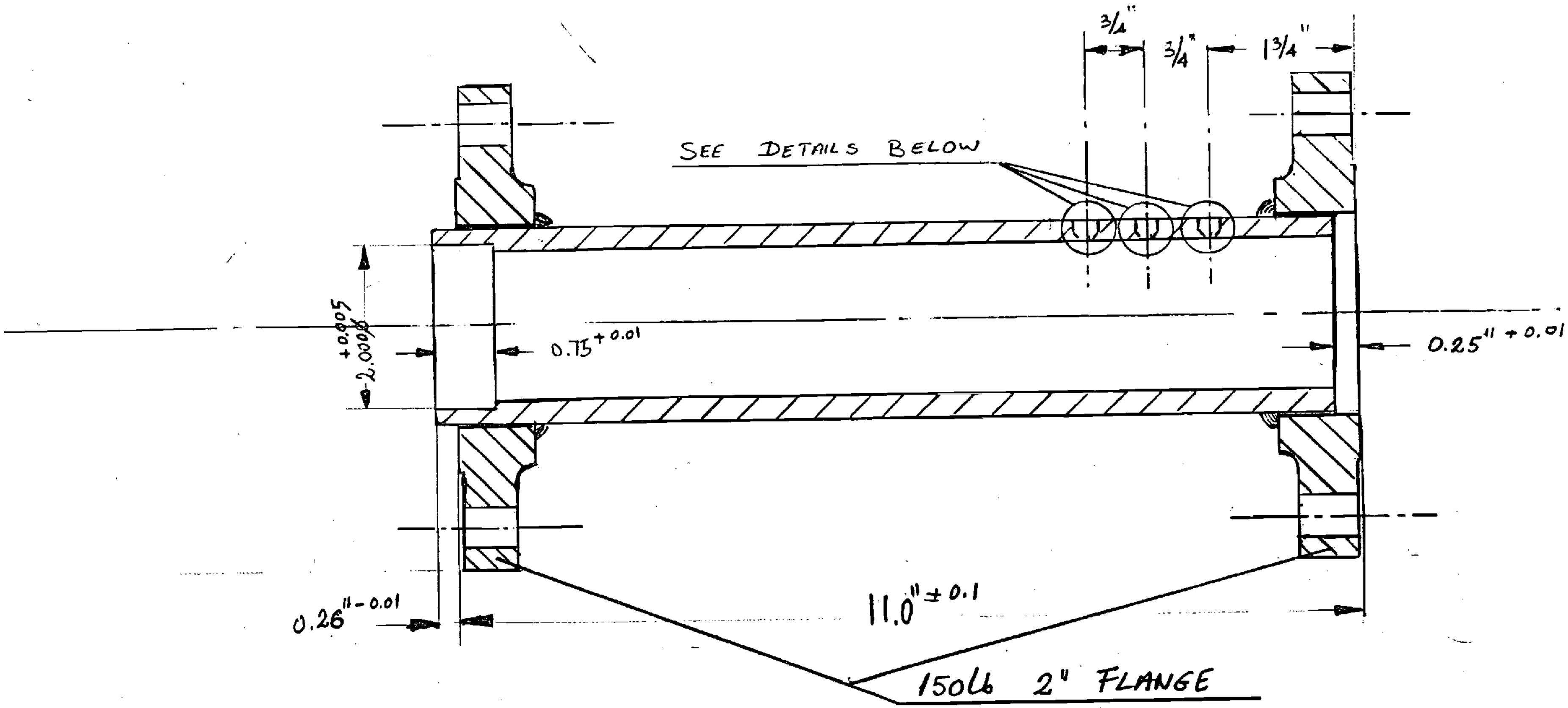

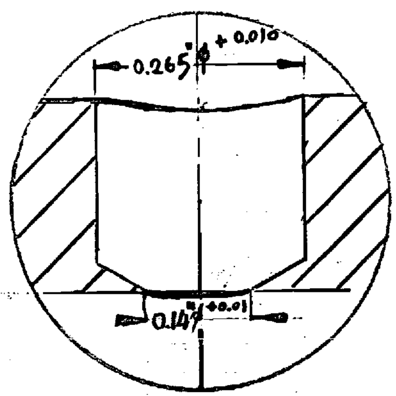

DETAILS OF HOLES IN TUBE

2×2" 150 lb flanges Carb. st. Tube, 2 3/8 OD - 1 7/8 ID	4	REUVEN	R. GAL-ED		E-16-
MATERIAL	NO. REQD.	DRAWN BY	APPROVED BY	ENG. CHK. BY	PROJ
SCALE 1:2	Catalytic Pulsed Combustor: Heater Holder				Drawing N E-16-621-1
DATE 10-22-85					

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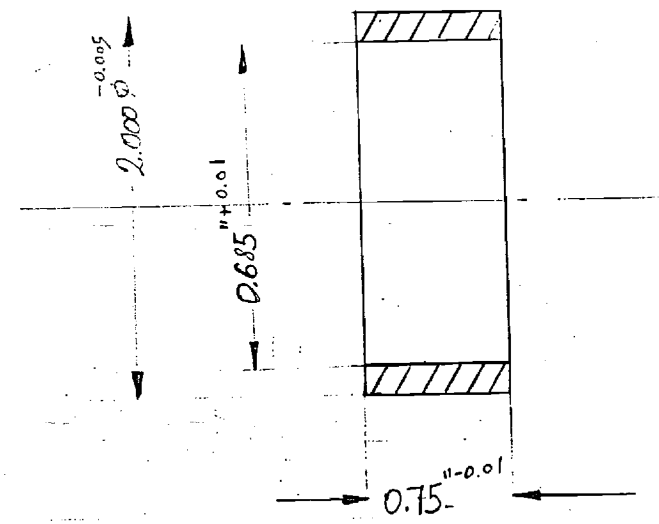

Carbon steel	4	REUVEN	R. Gal-Gal		E-16-
MATERIAL	NO. REQD.	DRAWN BY	APPROVED BY	ENG. CHK. BY	PROJ
SCALE 1:1	Catalytic Pulsed Combustor Stop for Heater (in Holder)				Drawing E-16-621-
DATE 11-26-85					

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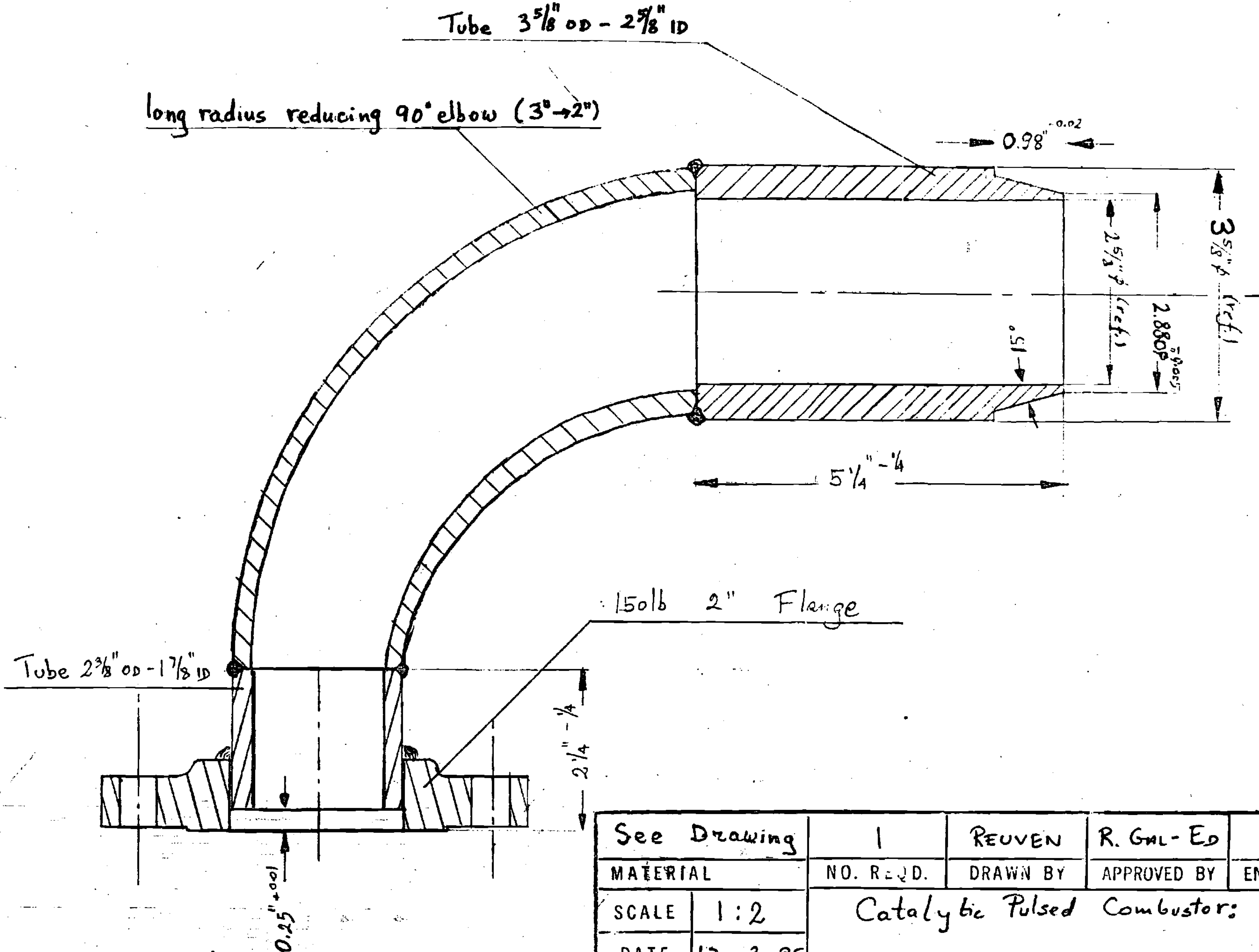

See Drawing	1	REUVEN	R. GAL-ED		E-16
MATERIAL	NO. REQD.	DRAWN BY	APPROVED BY	ENG. CHK. BY	PRO
SCALE 1:2	Catalytic Pulsed Combustor:				Drawing E-16-621-
DATE 10-3-85					

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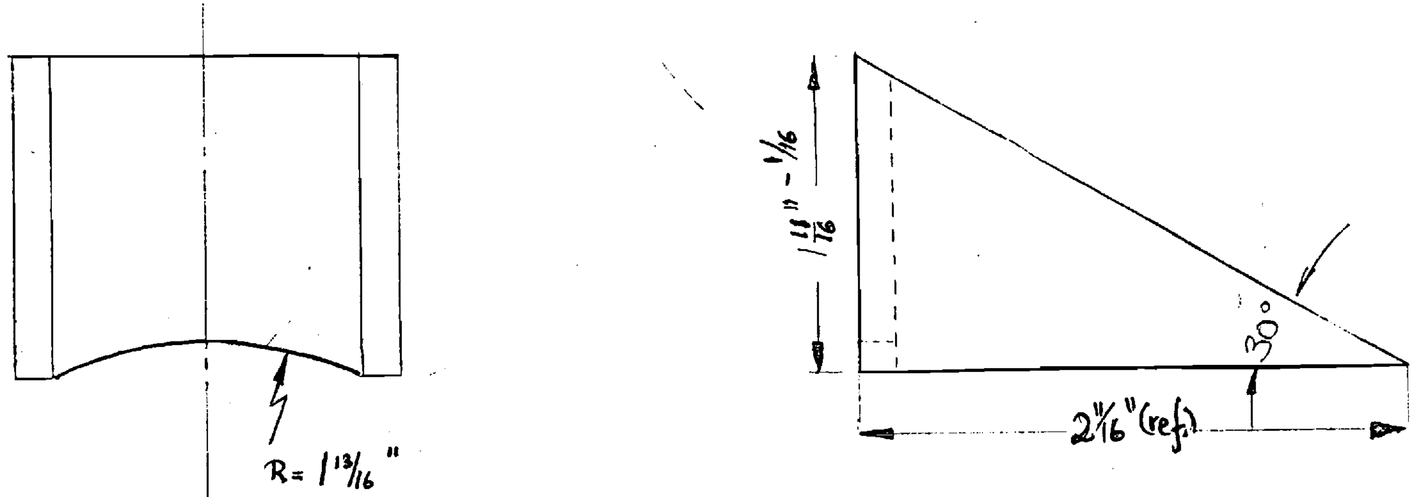

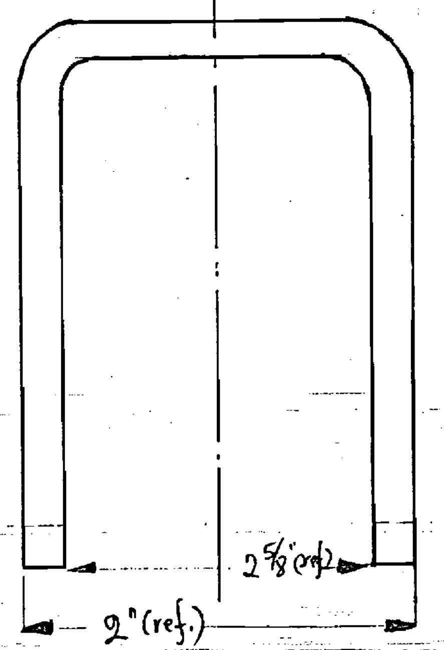

2" x 4" rec. shape	4	REUVEN	R. GAL-ED		E-16-6
MATERIAL	NO. REQD.	DRAWN BY	APPROVED BY	ENG. CHK. BY	PROJEC
SCALE: 1 : 1	Catalytic Pulsed Combustor: Clamping Ears				Drawing No
DATE: 10-23-85					E-16-621-22

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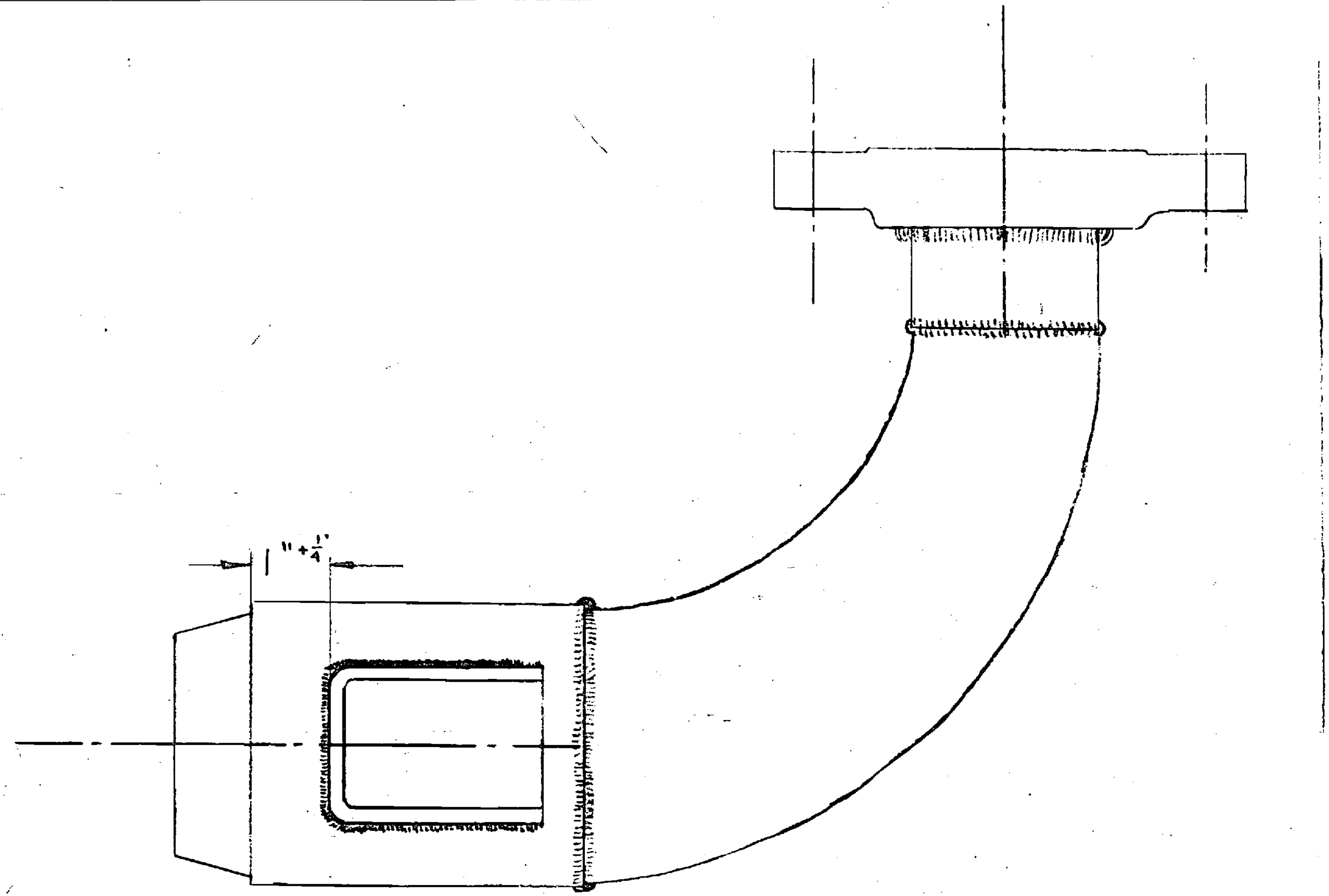

		REUVEN	R. GAL-ED		E-1
MATERIAL	NO. REQD.	DRAWN BY	APPROVED BY	ENG. CHK. BY	P
SCALE 1 : 2	Catalytic Pulsed Combustor:				Drawing
DATE 11-25-85	Location of Ear on Hot Air Inlet				E-16-621

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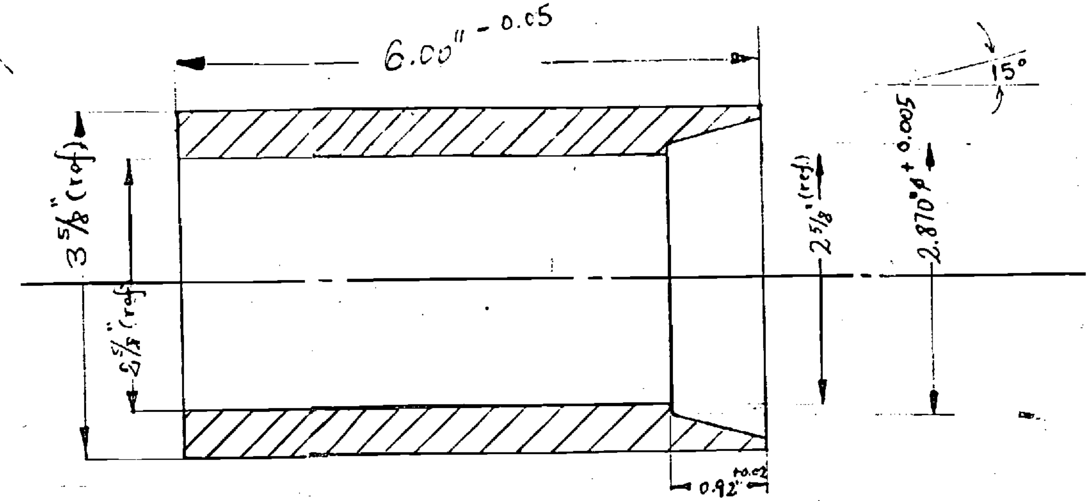

Carbon Steel tube $3\frac{5}{8}$" OD - $2\frac{5}{8}$" ID	1	REUVEN	R. GAL-ED		E-16-
MATERIAL	NO. REQD.	DRAWN BY	APPROVED BY	ENG. CHK. BY	PROJ
SCALE 1:2	Catalytic Pulsed Combustor: Exhaust Pipe				Drawing N E-16-621-
DATE 11-26-85					

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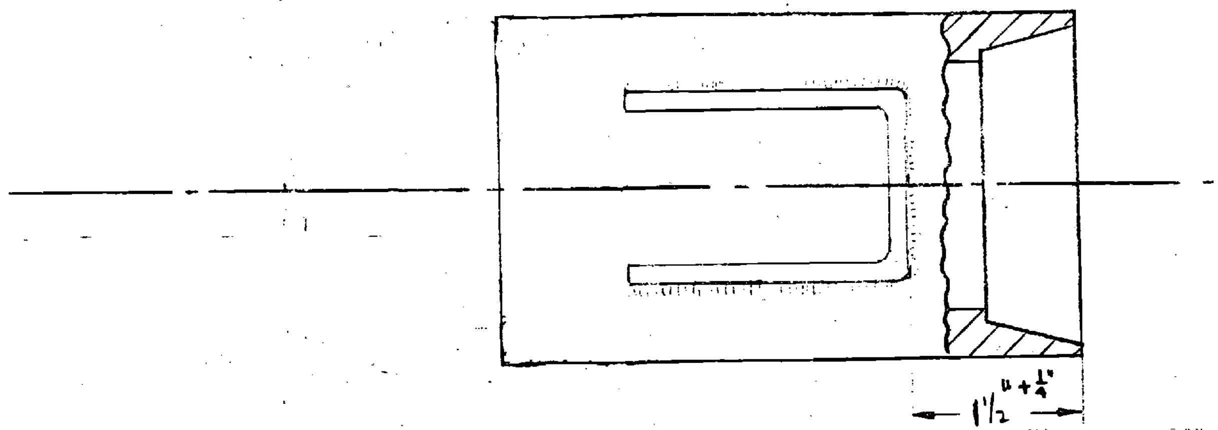

Exhaust Pipe + 2 Ears		REUVEN	R. Gal-Ed		E-16-6
MATERIAL	NO. REQD.	DRAWN BY	APPROVED BY	ENG. CHK. BY	PROJEC

SCALE	1 : 2	Catalytic Pulsed Combustor : Welding of Ears on Exhaust Pipe	Drawing No E-16-621-2
DATE	11-26-85		

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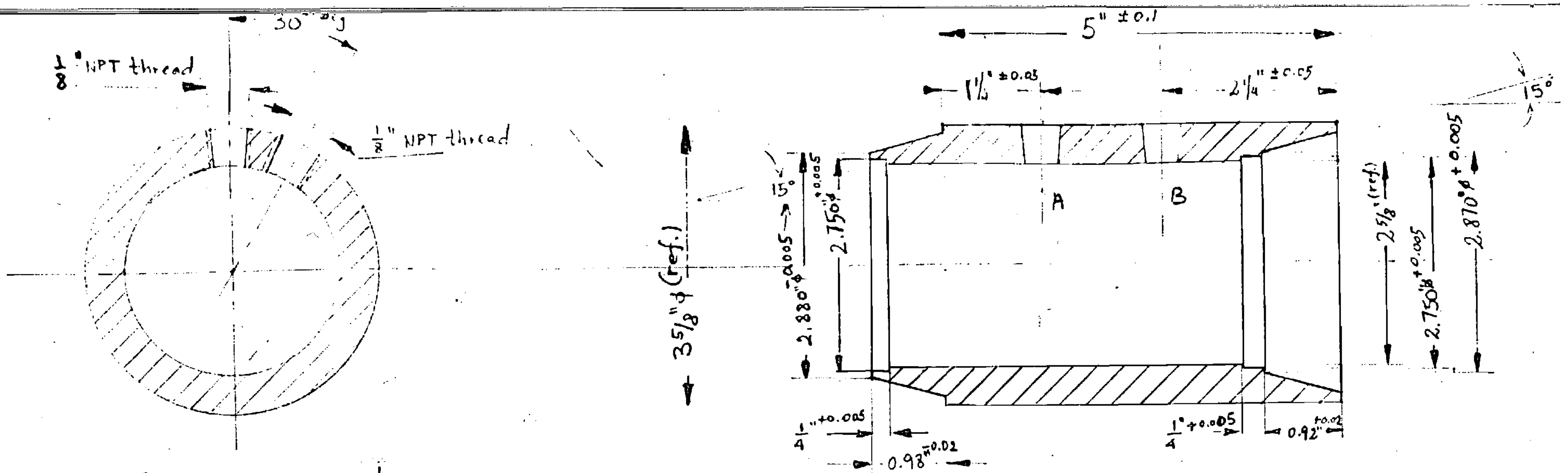

Typical cross section along A & B

Carbon steel Tube 3⅝" OD − 2⅜" ID	1	REUVEN	R. GAL-ED		E-16-62
MATERIAL	NO. REQD.	DRAWN BY	APPROVED BY	ENG. CHK. BY	PROJECT
SCALE 1:2	Catalytic Pulsed Combustor: Methane Injection Section				Drawing No E-16-621-30
DATE 9-13-85					

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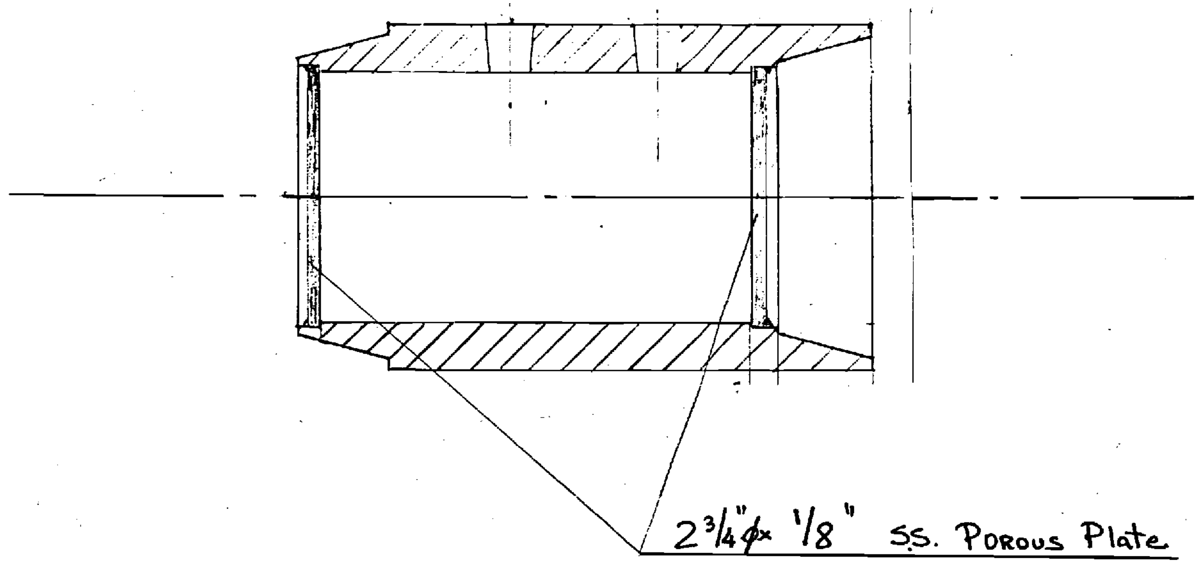

2 3/4" Dia Stainless Porous Plate	2	Reuven	R. Gal-Ed		E-16-621
MATERIAL	NO. REQD.	DRAWN BY	APPROVED BY	ENG. CHK. BY	PROJECT
SCALE 1:2 DATE 10-23-85	Catalytic Pulsed Combustor: Location of Porous Plates in Methane Injection Section				Drawing No E-16-621-33

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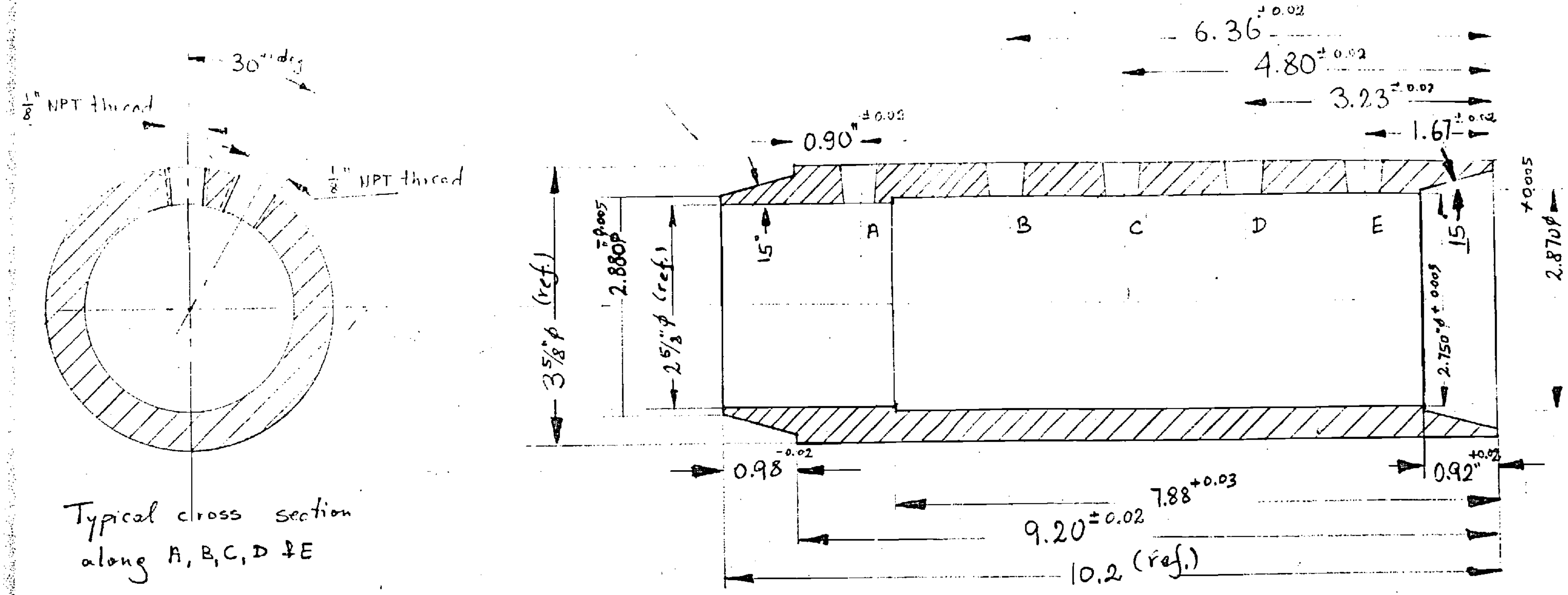

Carbon Steel Tube 3 5/8" OD - 2 5/8" ID	1	REUVEN	R. GAL-ED		E-16-
MATERIAL	NO. REQD.	DRAWN BY	APPROVED BY	ENG. CHK. BY	PROJ
SCALE 1:2	Catalytic Pulsed Combustor: Catalyst Section				Drawing E-16-621-
DATE 9-12-85					

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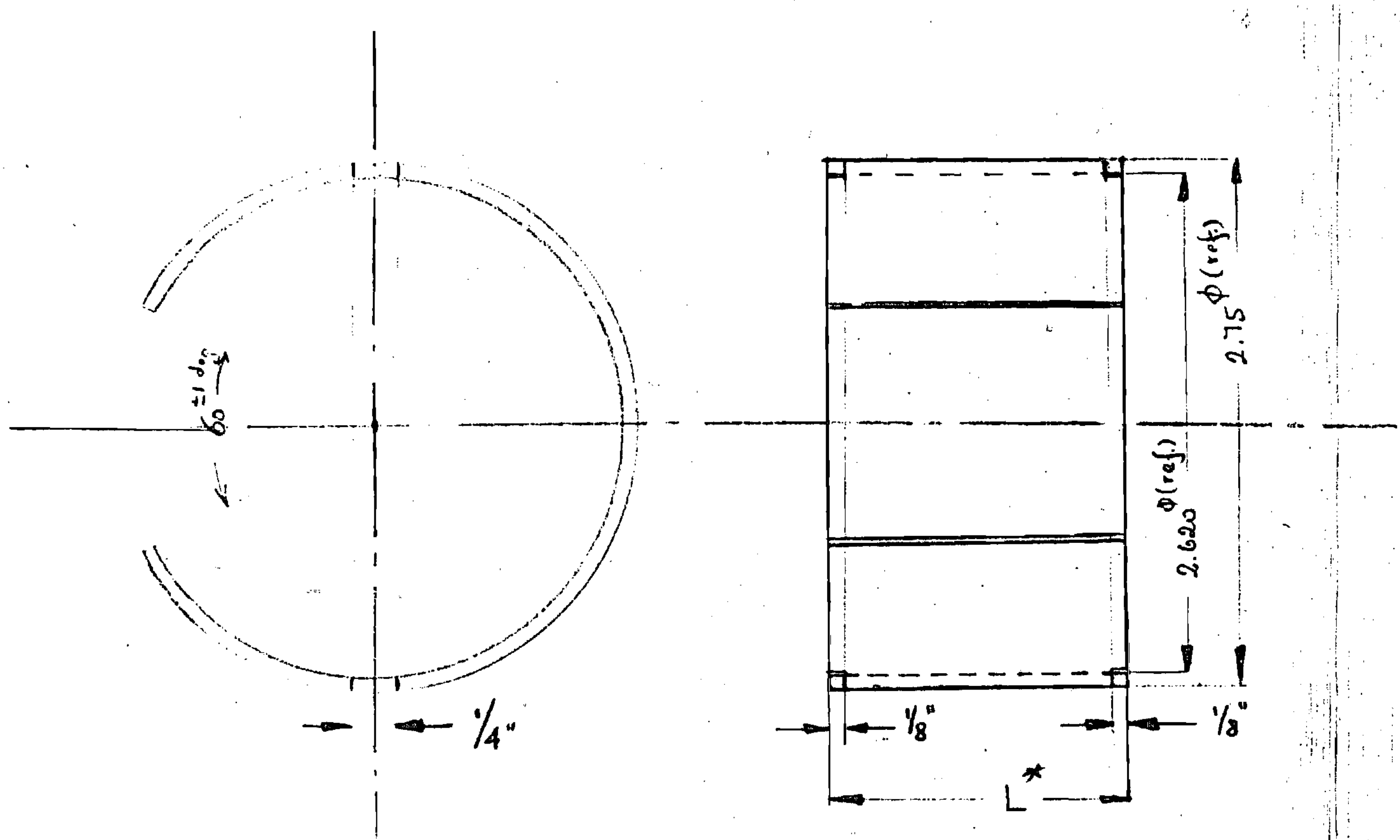

L	0.565" −0.005	1.30" −0.01
Quantity	4	1

1020 Tube 2 3/4" OD − 2.62" ID	4 + 1	REUVEN	R. GAL-ED		E-16-621
MATERIAL	NO. REQD.	DRAWN BY	APPROVED BY	ENG. CHK. BY	PROJECT
SCALE 1:1	Catalytic Pulsed Combustor: Spacers				Drawing No. E-16-621-42
DATE 9-13-85					

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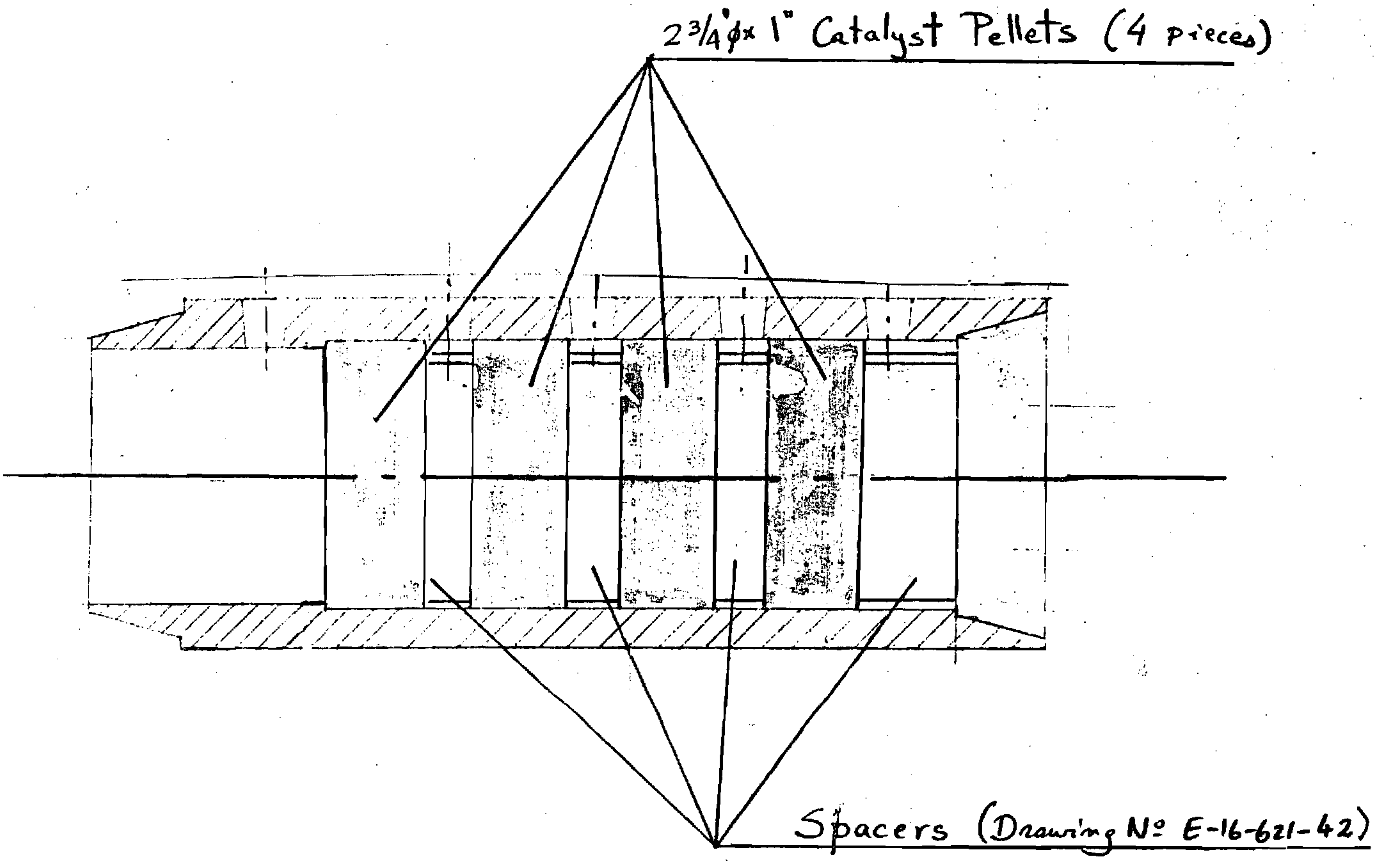

See Drawing		Reuven	R. Gm - Ld		E-16-621
MATERIAL	NO. REQD.	DRAWN BY	APPROVED BY	ENG. CHK. BY	PROJECT
SCALE 1:2	Catalytic Pulsed Combustor: Assembled Catalyst Section				Drawing No E-16-621-44
DATE 9-12-85					

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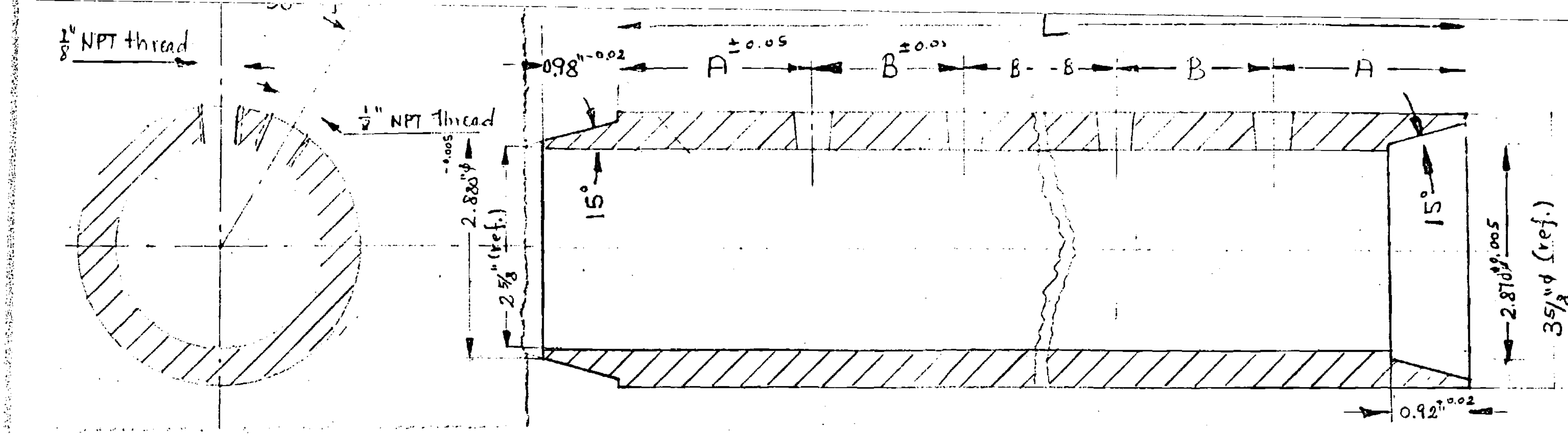

Typical cross section

L	A	B	No. of Sections	quantity
3"	1½"	–	1	1
6"	1½"	3"	2	1
9"	1½"	3"	3	1
12"	2"	4"	3	1
24"	3"	6"	4	1
40"	5"	6"	6	1
80"	5"	10"	8	1

Carbon Steel Tube 3 5/8" OD - 2 5/8" ID	7 - see list	REUVEN	R. GAL-ED		E-16-
MATERIAL	NO. REQD.	DRAWN BY	APPROVED BY	ENG. CHK. BY	PROJE

SCALE	1 : 2	Catalytic Pulsed Combustor: Variable Acoustic Tube Sections	Drawing N
DATE	9-13-85		E-16-621-

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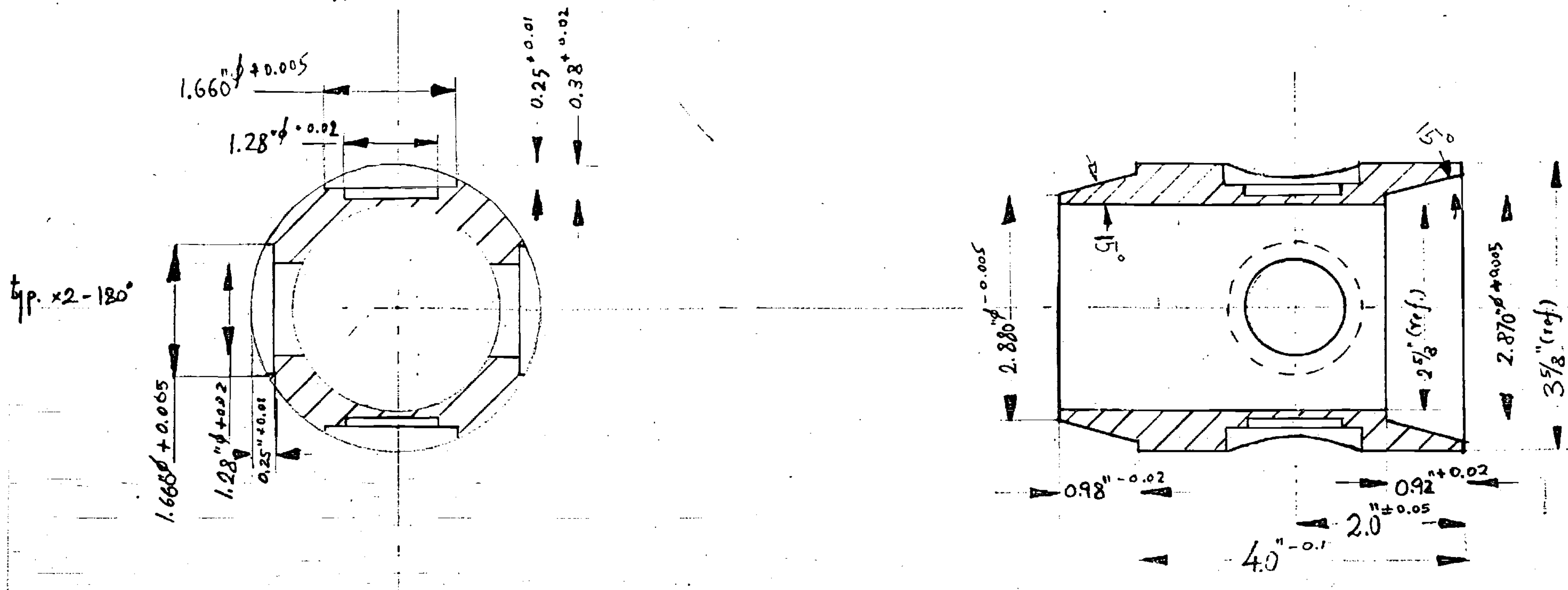

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MATERIAL	NO. REQD.	DRAWN BY	APPROVED BY	ENG. CHK. BY	PROJECT
SCALE 1:2	Catalytic Pulsed Combustor:			Drawing № E-16-621-50	
DATE 9-19-85	Acoustic Drivers Coupler				

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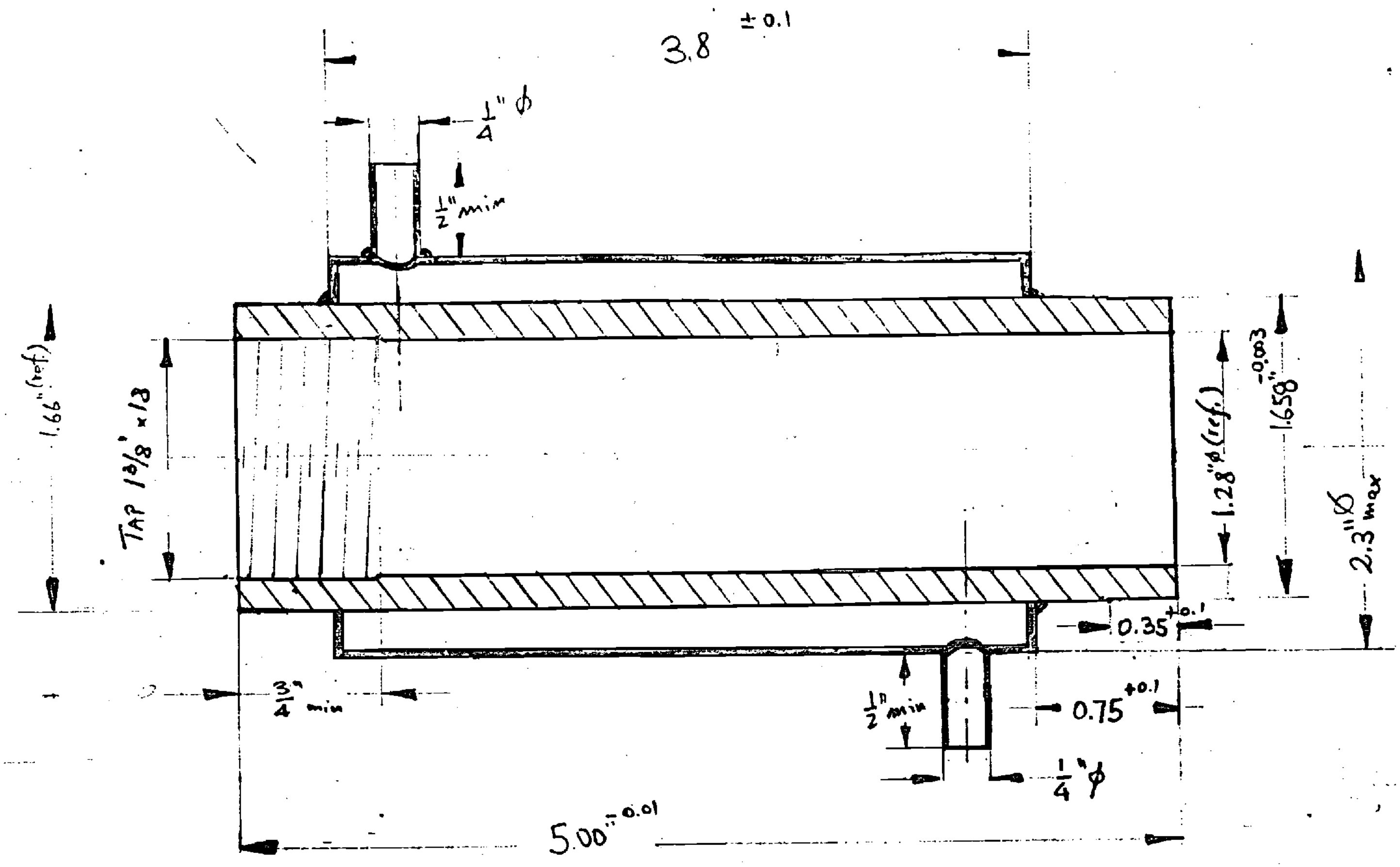

1 1/4" - sch. 80 pipe	4	Reuven	R. Gal-Ed		E-16-62
MATERIAL	NO. REQD.	DRAWN BY	APPROVED BY	ENG. CHK. BY	PROJECT
SCALE 1:1	Catalytic Pulsed Combustor:				Drawing №
DATE 9-19-85	Acoustic Driver Mount and Cooler				E-16-621-53

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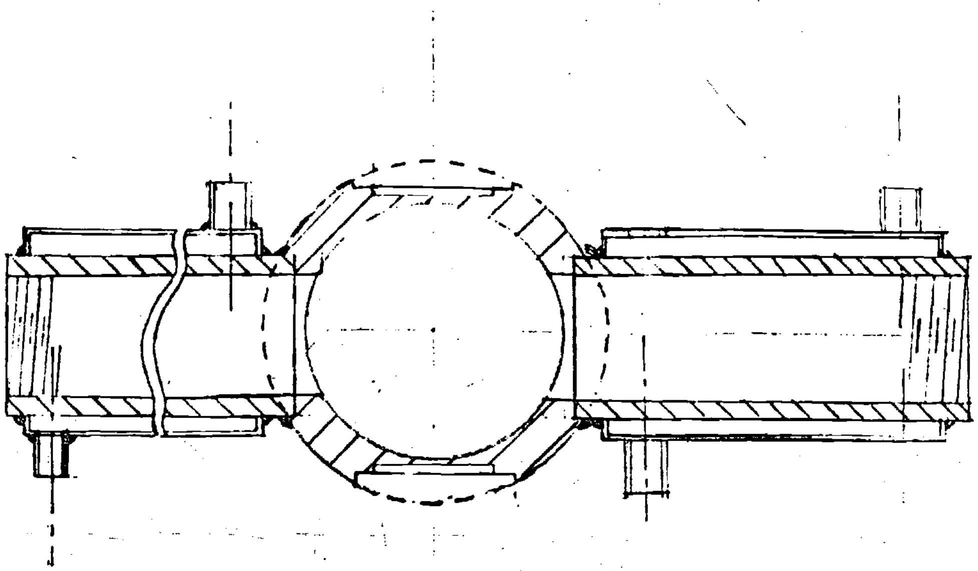

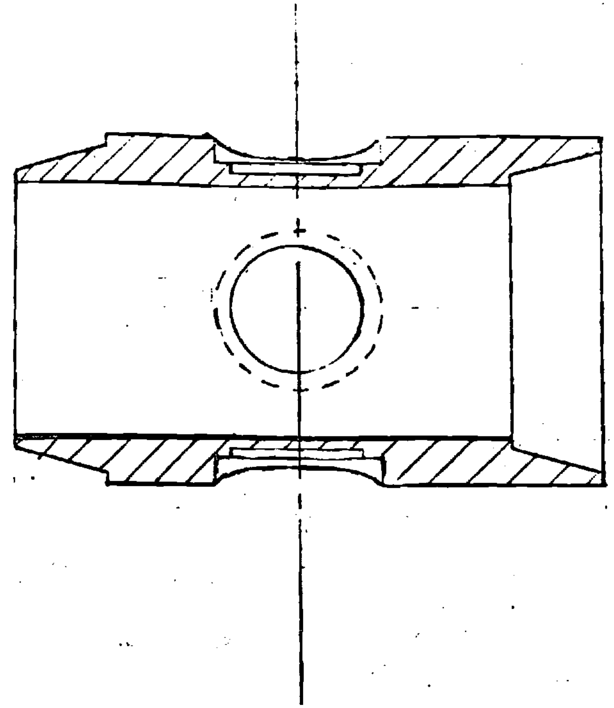

	1	REUVEN	R. GAL-ED		E-16-6
MATERIAL	NO. REQD.	DRAWN BY	APPROVED BY	ENG. CHK. BY	PROJE
SCALE 1 : 2	Catalytic Pulsed Combustor:				Drawing №
DATE 9-18-85	Acoustic Driver Mounting Scheme (2 Drivers)				E-16-621-5

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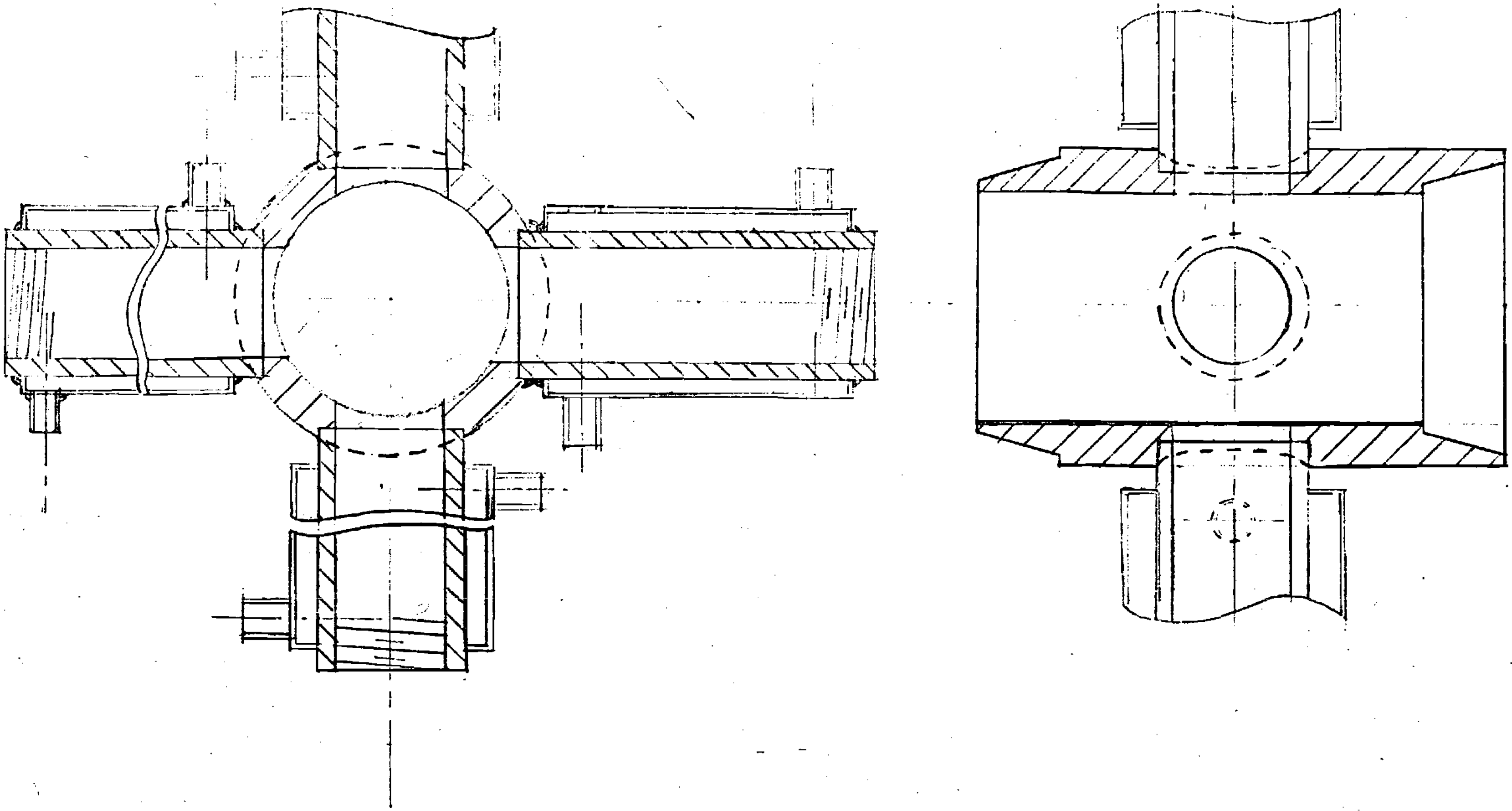

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	1	REUVEN	R. GAL-ED		E-16-6

SCALE	1 : 2	Catalytic Pulsed Combustor: Acoustic Driver Mounting Scheme (4 Drivers)	Drawing № E-16-621-58
DATE	9-18-85		

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E-16-621

CATALYTIC PULSE COMBUSTION

Third Quarterly Report
April 1986 - June 1986

Prepared by

B. T. Zinn, B. R. Daniel and R. Gal-Ed

School of Aerospace Engineering
Georgia Institute of Technology
Atlanta, GA 30332

Gas Research Institute
Contract No. 5085-260-1172

GRI Project Managers
James A. Kezerle
Robert V. Gemmer

July 1, 1986

RESEARCH SUMMARY

Title	Catalytic Pulse Combustion
Contractor	Georgia Tech Research Institute
Contract Number	GRI Contract 5085-260-1172
Report Period	April 1986 to June 1986 Third Quarterly Report
Principal Investigator	B. T. Zinn and B. R. Daniel
Objectives	The objective of this study is to investigate whether the performance of catalytic combustors can be improved by operating them under pulsating flow conditions.
Technical Perspective	Catalytic combustion processes involve both heterogeneous surface reactions and homogeneous gas phase reactions.

At low temperatures (i.e., T < 1000^{o}K) the gas phase reaction rate is negligible and the combustion occurs primarily at the catalyst surface. If the combustible mixture enters the catalyst section at a temperature that is considerably above the "light on" temperature (T > 800^{o}K), the diffusion processes of reactants and combustion products between the surface and the gas bulk are rate controlling. However, based upon earlier mass transfer studies in oscillating environments, it is expected that operating the catalytic combustor under pulsating conditions will enhance mass transfer rates to and from the catalyst surface and thus increase the apparent surface reaction rate.

As flow proceeds along the catalyst, the bulk gas temperature increases due to heat transfer from the catalyst surface. This, in turn, promotes gas phase reactions at the downstream section of the catalyst. If the catalyst is operated under pulsating conditions, the pulsations are expected to enhance heat transfer from the catalyst walls to the gas phase thus shortening the induction length of the gas phase reactions.

It is, thus, expected that operating the catalytic combustor under pulsating conditions will increase the output of the catalytic combustor, and/or decrease the amount of catalyst and size of combustion needed for a certain reactant flow rate.

Technical Approach

In the first phase of this study an experimental setup is being developed which will be used to investigate the dependence of a catalytic combustor performance upon the fuel/air ratio, the mixture flow rate, the mixture inlet temperature, the pulsation's frequency and amplitude, and the location of the catalyst section on the standing acoustic wave. Methane/air mixtures will be investigated and the catalyst performance will be determined from temperature and exhaust gas composition measurements. The effect of pulsations will be determined by comparing the combustor performance under steady and pulsating operating conditions.

Program Plan The program is divided into two major tasks which are briefly described below:

Task I - Development of the Experimental Setup.

A Determination of range of investigated test conditions and measurements to be performed.

B Design of the experimental setup.

C Fabrication of the experimental system.

D Assembly and checkout of the experimental setup.

Task II - Test Program.

A Determine the steady state combustion characteristics of the developed catalytic combustor.

B Investigate the dependence of the catalytic combustor performance upon the amplitudes and frequencies of the pulsations when burning lean mixtures and the catalyst is located at a pressure node.

C Investigate the dependence of the catalyst performance upon its location within the acoustic field.

D Investigate the dependence of the pulsating catalytic combustor performance upon mixture composition and its initial temperature.

Results

During the period 4/1/86 to 6/30/86 the assembly of the experimental setup was completed. In addition, setup checkout tests were performed. The latter indicated the need for modifications which were incorporated into the developed test setup. Finally, work has been initiated on the development of a computerized data acquisition system.

INTRODUCTION

Catalytic combustors offer specific advantages for a variety of applications. For example, the lower temperature of their exhaust gases makes them suitable for gas turbines; the low levels of concentration in their exhaust products makes them attractive from an environmental point of view; and their ability to burn extremely lean fuel/air mixtures enables them to recover energy which otherwise would be wasted.

Under many operational conditions, the output of catalytic combustors is limited by the rate of diffusion of the reactants and products to and from the catalysts surface, respectively. The chemical reactions in the upstream section of the catalytic combustor occur mostly on its surface. The heat released on the catalyst surface is transferred, however, to the flowing gas stream at some downstream station. The resulting heating of the gas phase leads to the occurrence of homogeneous gas phase reactions in the downstream section of the catalytic combustor. The location where these gas phase reactions are initiated depends upon the rate of heat transfer from the catalyst surface and the gas phase. Consequently, to increase the output of catalytic combustion one has to find means for increasing the rate of mass and heat transfer to and from the catalyst. In related studies, it has been shown that both heat and mass transfer processes are enhanced when they occur in an acoustic field. In view of these observations, the present study will investigate whether the performance of catalytic combustors can be improved by operating them under pulsating conditions. More specifically, this study will investigate the ranges of amplitudes and frequencies which optimize the operations of catalytic combustors.

OBJECTIVES

The objective of this research program is to determine whether the performance of catalytic combustors burning lean methane/air mixtures can be improved by operating then under pulsating conditions. The extent of the resulting improvements will be determined by comparing the performance of the investigated catalytic combustor when operating under pulsating and steady state conditions. Furthermore, the dependence of the combustor performance upon the amplitude and frequency of pulsations, at the location of the catalyst within the acoustic field will be investigated.

TECHNICAL PROGRESS

Work performed during the reporting period (April - June 1986) concentrated on completing the development of the experimental setup. Specifically, the following tasks were performed during the reporting period:

A.- Completing the Assembly of the Experimental Setup.

These efforts included the installation of the electrical heaters, the assembly and installation of the catalytic combustor section, and the assembly and installation of the methane line.

B.- Checkout Tests.

B.1 - Air Line: The combustion air supply line was tested. These tests showed that large pressure drops occurred across the two porous plates which are located at both ends of the methane injection/mixing section. These porous plates serve as safety devices to prevent upstream flame propagation from the combustor section into the mixing section and prevent methane from diffusing into the heater section. The presence of such large pressure drops across these porous plates would have prevented accurate flow rate measurements by the available rotameter and would have prevented the attainment of high velocities in the combustor due to the existing air supply pressure limitations. The installed plates were replaced by new, thinner, special stainless steel plates with a higher porosity. Tests with the new plates showed that they produced considerably lower pressure drops which resulted in a satisfactory system performance.

B.2 - Methane Line: The methane supply line was tested for leaks and to determine its flow characteristics using air. Leaks were detected and corrected. The rotameter, the pressure regulator, the backup pressure valve, and the shut-off solenoid valve were tested and found to operate satisfactorily. Upon completion of these tests the methane bottle was connected to the line and the system was rechecked for leaks.

B.3 - Air Heaters: The performance of the installed air heaters was tested and it was found that an air temperature of 600^{o}C or higher can be reached at the methane injection section at all desired air flow rates.

B.4 - Acoustic Drivers: The acoustic wave driving consists of a function generator, a 100W amplifier and two acoustic drivers. This system was checked by operating it over prolonged periods of time in the frequency range of 200 - 1500 Hz which will be used in the proposed tests. In addition, the driving system was operated for short periods of time (i.e., one minute) in the frequency range of 100 - 200 Hz.

C. Checkout of the Data Acquisition System.

C.1 - The Data Logger: In checkout tests of the recently acquired Lecroy data Logger it was found that the software controlling the system can access only 4 memory modules (i.e., 126 Kbytes of data) instead of all 8 modules, and the maximum sampling frequency was 20

KHz instead of the specified 40 KHz. A computer software specialist has been hired and he is currently working on the resolution of these problems which will enable the utilization of the full capability of the system during the proposed tests. It should be pointed out that in the meantime the data logger may be used with its limited capabilities.

C.2 - The ILS Software: This is a recently acquired (for this program) library of subroutines intended for analysis of random and periodic data, storing files (either sampled data or manipulated results) and plotting of the information. The use of the various subroutines was studied and a framework for the measurement and analysis of the excited acoustic waves was developed. Current efforts are concerned with the development of software for the acquisition and analysis of acoustic data in the developed experimental setup.

C.3 - Temperature Data Acquisition: Current efforts investigate the interface hardware which should be used for temperature data acquisition. This hardware will connect the various Chromel-Alumel thermocouples to the data logger's A/D converter. The framework for the temperature acquisition and analysis was developed and once a decision regarding the needed hardware is reached the needed software would be written.

D. - Status of Experiment.

The assembly of the experimental setup and most of the checkout tests have been completed. The majority of current efforts are concerned with the development of the needed data acquisition system. The test program will be initiated as soon as these efforts are completed.

PLANNED WORK

The development of needed software for acoustic pressure data acquisition and analysis will be completed within the next 4-8 weeks. These efforts will be followed by tests designed to determine acoustic losses (or attenuation) in the combustor section at different frequencies to be employed in this program. Upon completion of these tests, the steady state performance characteristics of the developed combustor will be investigated.

CATALYTIC PULSE COMBUSTION

FINAL REPORT

(October 1985 - December 1986)

Gas Research Institute
8600 West Bryn Mawr Avenue
Chicago, Illinois 60631

Catalytic Pulse Combustion

Final Report
October 1, 1985 - December 31, 1986

Prepared by

B. T. Zinn, B. R. Daniel and R. Gal-Ed

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For

Gas Research Institute

Contract No. 5085-260-1172

GRI/87-0042

GRI Project Managers

James A. Kezerle

Robert V. Gemmer

Combustion

May, 1987

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7. Author(s) B. T. Zinn, B. R. Daniel and R. Gal-Ed	8. Performing Organization Rept. No.
9. Performing Organization Name and Address School of Aerospace Engineering Georgia Institute of Technology Atlanta, GA 30332	10. Project/Task/Work Unit No. 11. Contract(C) or Grant(G) No. (C) GRI 5085-260-1172 (G)
12. Sponsoring Organization Name and Address Gas Research Institute 8600 West Bryn Mawr Avenue Chicago, Illinois 60631	13. Type of Report & Period Covered Final Report 10-1-1985 to 12-31-1986 14.

15. Supplementary Notes

16. Abstract

Increasing the rate of combustion within catalytic combustors would increase their output and or reduce their size; advantages which may result in increased productivity and cost reduction. This report describes initial results of an experimental investigation of the effect of pulsations upon the performance of catalytic combustors. This investigation had been inspired by previous studies which showed that flow pulsations enhance the rates of heat and mass transfer between flows and surfaces; processes which control the output of catalytic combustors. This report describes the experimental setup which had been specifically developed for this study. It possesses capabilities for operating the catalytic combustor section, which consists of four monolithic catalyst discs, under pulsating and nonpulsating conditions. Furthermore, it possesses capabilities for varying the initial mixture temperatures, the fuel/air ratios, the flow rates, the amplitudes and frequencies of pulsations and the catalytic combustor location on the excited acoustic wave. Initial tests have shown that operating the catalytic combustor under pulsating conditions produces frequency dependent temperature changes within the catalytic combustor section. This result indicates that pulsations influence the catalyst combustion processes and may improve its performance.

17. Document Analysis a. Descriptors

b. Identifiers/Open-Ended Terms

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RESEARCH SUMMARY

Title	Catalytic Pulse Combustion
Contractor	Georgia Tech Research Institute
Contract Number	GRI Contract 5085-260-1172
Report Period	October 1985 - December 1986 Final Report
Principal Investigator	B. T. Zinn and B. R. Daniel
Objective	The objective of this study is to investigate whether the performance of catalytic combustors can be improved by operating them under pulsating conditions.
Technical Perspective	Catalytic combustion processes involve both heterogeneous surface reactions and homogeneous gas phase reactions. At relatively low temperatures (i.e., $T < 1000°K$) the gas phase reaction rate is negligible and the combustion occurs primarily at the catalyst surfaces. If the combustible mixture enters the catalyst section at a temperature that is considerably above the "light on" temperature (i.e., $T > 800°K$), the diffusion processes of reactants and combustion products between the surfaces and the gas stream are rate controlling. However, based upon earlier mass transfer studies in oscillating environments, it is expected that operating the catalytic combustor under pulsating conditions will

enhance mass transfer rates to and from the catalyst surfaces and thus increase the apparent surface reaction rate.

As the flow proceeds along the catalytic combustor, the gas phase temperature increases due to heat transfer from the hot catalyst surfaces. This, in turn, promotes gas phase reactions in the downstream section of the catalytic combustor. If the catalyst is operated under pulsating conditions, the pulsations are expected to enhance the rate of heat transfer from the catalyst surfaces to the gas stream, thus shortening the induction length of the gas phase reactions.

In summary, it is expected that operating a catalytic combustor under pulsating conditions will increase its output or decrease the amount of catalyst surface and size of combustor required for a given reactant flow rate.

Results

During the reporting period the development of the experimental setup has been completed and some initial tests have been conducted. These tests, conducted with lean methane/air mixture, showed that under certain operating conditions the excitation of acoustic oscillations in the catalytic combustor section can cause both increases and decreases in temperatures downstream of the various catalyst sections. These temperature variations are frequency dependent. The mechanisms responsible for these temperature variations and their implications are presently not understood. However, the observed temperature increases suggest that operating catalytic combustors in an acoustic field may improve their performance.

Technical Approach

The first phase of this study involved the development of an experimental setup for the investigation of catalytic combustion of lean methane/air mixtures under pulsating and nonpulsating conditions. This set up could be used to determine the dependence of the catalytic combustor performance upon the methane/air ratio, the mixture flow velocity, the mixture inlet temperature, the pulsations' frequency and amplitude and the location of the catalyst surfaces on the standing acoustic wave. Initially, the catalytic combustor performance will be determined from temperature and exhaust gas composition measurements. The effect of pulsations will be determined by comparing the combustor performance under steady and pulsating flow conditions.

Project Implications

The results from this research demonstrate that the imposition of acoustic pulsations on a combustion catalyst can cause a significant modification of the catalyst's performance, as measured by changes in the temperature of the catalyst. However, the extent of the changes in catalyst performance, and the dependence of those changes on the frequency, amplitude, and phase of the pulsations are still not well characterized. Before the use of pulsating catalytic combustion can be meaningfully evaluated, more detail about the phenomena needs to be developed. A follow-on contract with these investigators has been initiated to develop the needed additional understanding. The ultimate disposition of this research, whether more applied, or basic, or both, will depend on the outcome of the continuing research.

Robert V. Gemmer
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Physical Sciences Department

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INTRODUCTION

Catalytic combustors offer specific advantages for a variety of applications. For example, the lower temperature of their exhaust gases makes them suitable combustors for gas turbines; the low level of pollutant concentrations in their exhaust products makes them attractive from an environmental point of view; and their ability to burn extremely lean fuel/air mixtures enables them to recover energy which otherwise would be wasted.

At high operating temperatures, the output of catalytic combustors is limited by the rate of diffusion of the reactants to the catalyst surface. Generally the chemical reactions in the upstream section of a catalytic combustor occur mostly on its surface. A portion of the heat released on the catalyst surface is transferred to the flowing gas stream. The resulting heating of the gas phase leads to homogeneous gas phase reactions in the downstream section of the catalytic combustor. The location where these gas phase reactions are initiated depends, among other factors, upon the rate of heat transfer from the catalyst surface to the gas stream. Consequently, by finding means for increasing the rates of mass and heat transfer to and from the catalyst surface, it may prove possible to increase the output of a catalytic combustor.

In related studies [1,2,3], it has been shown that the rates of both convective heat transfer and mass transfer processes are increased when they occur in oscillating flow environments (e.q., acoustic fields). These observations suggest that the performance of catalytic combustors could be improved by operating them under pulsating conditions. The present study had been undertaken to determine the feasibility of this idea. Specifically, the objective of this study is to establish the dependence of the performance of a catalytic combustor upon the frequencies and amplitudes of the pulsations and the location of the catalyst surface relative to the imposed standing acoustic wave. The effect of pulsations will be assessed by comparing the performance of the catalytic combustor when operated under pulsating and nonpulsating conditions.

RESEARCH PLAN

This research has been divided into three major tasks which are briefly described below:

Task I - Development of the Experimental Setup

A. Determination of Test Setup Configuration and Test Conditions:

In this subtask the characteristics (e.g., the major components, their dimensions, etc.) of the needed experimental setup, ranges of test conditions (e.g., flow velocities, mixture inlet temperature, etc.) and the data to be measured (e.g., pressures, compositions, etc.) were to be determined. These choices were based upon reviews of previous studies of the performance of nonpulsating catalytic combustors [4], consideration of the objectives of this research program and existing experimental capabilities.

B. Design of the Experimental Setup:

In this subtask the detailed design of the experimental setup was to be established. This effort was guided by results of previous studies of the performance of catalytic combustors and pulsating combustion systems, and decisions made (see subtask A above) regarding the conditions to be investigated.

C. Fabrication of Components:

The combustor components were to be fabricated in the departmental machine shop.

D. Development of Required Measurement Capabilities:

This subtask involved development of capabilities for measuring fuel and air flow rates, temperatures, acoustic pressures, and chemical compositions of the combustion products.

E. Development of Computer Based Data Acquisition System:
The anticipated need for multi-channel measurements for prolonged periods of time called for the development of a computer based data acquisition and reduction system. To meet this need, a computer, a data logger and related software were to be acquired and connected to existing data acquisition equipment, forming a flexible computer-based system. The data acquired and stored by the logger will be transferred to the computer storage discs and subsequently reduced to a desired form by the computer.

Task II - Experimental Investigation

A. Catalytic Combustor Performance Under Nonpulsating Conditions:
The steady state performance of the catalytic combustor was to be determined while operating the pulse combustor without acoustic excitation. The measured steady-state performance will be used as a reference for comparison with the catalytic combustor performance when operated under pulsating conditions. These investigations were to be performed at a specified, lean methane/air ratio which is below the lower flammability limit. A very lean methane/air mixture will be investigated to avoid (or minimize) the occurrence of gas phase reactions. This will (possibly) limit the investigation to heterogeneous surface reactions only. The mixture flow rate (and its resulting velocity) is the only parameter to be varied in this phase of the study.

B. <u>Effect of Pulsations on the Catalytic Combustion</u>:

The performance of the catalytic combustor under pulsating conditions is determined by systematically varying the following parameters:

B.1 - The Frequency of Pulsations. In the first stage of this study the dependence of the catalytic combustor performance upon the frequency of the excited acoustic wave will be established. In this study, efforts will be made to keep the catalyst segments in the vicinity of either a pressure node or a pressure antinode, to maintain the amplitude of the excited acoustic waves constant and to keep the reactants flow rate fixed.

B.2 - The Amplitude of Pulsations. In the next series of tests the effect of varying the amplitude of pulsations upon the catalytic combustor performance will be determined. These tests will be conducted at a frequency which strongly affects the combustor performance, as determined in B.1 above.

B.3 - The Location of the Catalyst Section. In the third series of tests the effect of the location of the catalyst section on the standing acoustic wave will be determined. Specifically, this study will determine the performance of the catalytic combustor when the catalysts are located at a pressure node, a pressure antinode and at locations between these two. These tests will be conducted at a specific amplitude which is selected from those investigated in the series of tests described in B.2 above. The frequency and all other parameters will be kept unchanged, while the catalyst section is moved along the combustor.

B.4 - The Mixture Velocity. In this series of tests the effect of the methane/air flow velocity (and, thus, its residence time in the catalyst section) on the performance of the catalytic combustor under pulsating conditions will be established. This study is conducted at specific pulse combustor operating conditions which are selected based upon results obtained in earlier studies.

B.5 - The Methane/Air Mixture Composition. In this study, the dependence of the catalytic combustor performance upon the mixture composition will be established. It is expected that the combustor performance will depend on whether reactions occur on the catalyst surfaces only or both on the catalyst surfaces and in the gas phase. At very lean mixtures reactions are expected to occur on the catalyst surfaces only. However, as the methane concentration is increased beyond the lower flammability limit, gas phase reactions are also expected to occur due to the transfer of heat from the catalyst surfaces to the gas phase. Since pulsations are expected to affect both mass and heat transfer rates, their effect upon the combustor performance is expected to depend on the mixture composition which determines whether surface reactions only or both surface and gas phase reactions occur in the catalytic combustor.

B.6 - The Mixture Inlet Temperature. In this study the effect of the temperature of the reactants at the inlet to the catalytic combustor upon the performance of the catalytic pulse combustor will be determined.

B.7 - Final Checkout Tests. In this effort, trends found in previous studies will be checked out by measuring the performance of the combustor at several other combinations of test conditions.

Task III- Reporting

As per contract agreement.

PROGRESS AND RESULTS

Work performed during the reporting period (October 1985 to December 1986) included the development of the experimental setup and the conduct of preliminary experiments. Specifically, the following tasks were performed:

A. Determination of Experimental Setup Configuration and Test Conditions. The design of the various components and subsystems of the developed experimental setup is described in this section.

A.1 The Catalyst Section. It consists of a carbon steel tube containing four one inch thick monolithic, circular catalyst segments arranged sequentially. The catalysts are separated by distances of 0.625 inch from one another. Reaction occurs as the gas flows from one catalyst segment to another. The chosen catalyst section design will remain unchanged throughout this study. The monolith type catalysts that were used were supplied by the Alzeta Corporation and are made of an alumina honeycomb coated with platinum.

A.2 The Combustible Mixture. The investigated gas mixtures consist of technical grade methane (from pressurized bottles) and compressed air. The use of no other fuels and oxidizers is planned for this study. To avoid poisoning of the catalyst by carbon deposits, the combustion of only lean methane/air mixtures is being investigated in this study.

A.3 Experimental Setup. The catalytic combustor section consists of four one inch thick, circular (disc like) monolith catalyst sections inserted inside a 2.625 inch inside diameter carbon steel tube. The catalyst sections are separated by a distance of 0.625 inch from one another. Thermocouples and dynamic pressure transducers are installed upstream and downstream of each catalyst section to determine the temperatures and acoustic pressures at these locations. The catalytic combustor section can be inserted at different locations along the experimental setup, thus providing a capability for determining the effect of location of the catalytic combustor section relative to the standing acoustic wave upon the catalytic combustor performance.

A.4 Combustor Inlet Temperature. The methane/air mixture inlet temperature is controlled by four electric heaters, with a total output of 12 kilowatts, which heat the air to a desired temperature before it mixes with the methane. The heating system is controlled by a variable voltage regulator and a switching system. It is capable of heating the air to any desired temperature up to 600°C.

A.5 Flow Velocity. The flow velocities were limited to the range of 2.5 to 30 meters per second. This velocity range was determined from data obtained in related investigations of steady catalytic combustion [4].

A.6 Location of the Catalyst Section. During the current (initial) phase of testing of the catalytic combustor under pulsating conditions the catalyst section was placed at an acoustic pressure node where the acoustic velocity oscillations are maximum and where the acoustic effects are expected to be the largest. The experimental setup includes provisions for moving the catalyst section to other locations along the standing acoustic wave. Thus, tests can be performed with the catalyst section located at acoustic pressure nodes, pressure antinodes and locations in between these two for the entire range of contemplated frequencies.

A.7 Acoustic Power Generation. Acoustic pulsations are excited in the experimental setup by utilizing two University Sound electrical acoustic drivers which are controlled by a signal generator and a 100 watt amplifier. If needed, the system can be upgraded to 300 watts by use of two additional drivers and a more powerful amplifier. These drivers can excite acoustic waves in the 200 - 1500 Hz frequency range over long periods of time. Waves with frequencies outside this range can be excited for shorter time durations.

A.8 Acoustic Pressure Measurements. The characteristics of the excited acoustic field are measured by 10 piezo-electric pressure transducers attached to "semi-infinite tubes" to avoid damage to the transducers from the heat generated in the combustor and to provide a flat frequency response.

A.9 Temperature measurements. Temperatures are measured by type K (Chromel-Alumel) thermocouples, capable of measuring temperatures up to 1350°C. Capabilities for simultaneous measurements of up to 12 temperatures have been developed.

B. Design of the Experimental setup.

B.1 Description of Experimental Setup. A schematic of the experimental setup is shown in Figure 1. It consists of a vertical heating section where air enters at the top and passes through the four electric heaters which are assembled in flanged carbon steel pipe segments. The air leaves the heating section at the bottom at a predetermined temperature. The vertical heating section connects through an elbow to a horizontal pipe consisting of interchangeable segments. These interchangeable segments include the fuel injection and mixing section, the catalyst section, the acoustic excitation section and six pipe sections of different lengths which provide capabilities for positioning the catalyst section at any of several locations on the standing acoustic wave. The horizontal part of the combustor terminates with a short exhaust section. The exhaust pipe and the inlet elbow at the opposite ends of the horizontal section of the combustor are equipped with special anchors which are used to clamp the entire horizontal part and hold the interchangeable segments together. Drawings of all of these segments are provided in one of the previous progress reports [5]. The experimental setup is mounted on a mobile support structure made up of metal-lumber sections attached to four casters.

B.2 The Air Line. Combustion air is supplied by a 100 psig compressed air line. Prior to entering the combustor, the air passes through a filter to remove any particulates, condensed moisture or oil mist. Next, the air enters a flow rate measurement system consisting of a rotameter, a pressure regulator and a back-pressure valve (which are used to control the rotameter pressure), and pressure and temperature measuring devices. Upon leaving the flow rate measurement section, the air enters the heating section at the top of the vertical part of the combustor.

B.3 The Methane Supply System. Methane is supplied from a methane bottle via a pressure regulator to the methane flow rate measurement system which is similar to the air flow rate measurement system described above. Two safety devices, a flame arrestor, which prevents the propagation of the flame upstream in the methane line, and a shut-off solenoid valve, which can stop the fuel flow instantaneously, are installed in the methane line just before it enters the methane injection and mixing section in the horizontal part of the combustor.

B.4 Composition Measurements. A previously developed gas composition analysis system capable of measuring the concentrations of CO, CO_2, NO_x, SO_2, O_2, and hydrocarbons is currently in use in the Aerospace Engineering Combustion and Fluid Mechanics Laboratory. This system is available for use in the pulse combustion research program. The composition of the combustion products is generally used to determine the combustor efficiency and pollutant formation.

B.5 The Data Acquisition System. A 32 channel computerized data acquisition system is utilized to acquire and analyze the measured temperature, composition and acoustic pressure data.

B.6 The Electrical Power Supply. A 220 Volt, 60 Amp. line supplies the electric power to the electric air heaters. A 115 Volt line supplies power to the computerized data acquisition system and its accessories, to the shut-off solenoid valve and to the acoustic power generation system.

B.7 The Exhaust System. The exhaust section of the combustor connects to the inlet of an 8 inch circular duct attached to an exhaust fan. The fan pumps the combustion products generated in the catalytic combustor and room air into the 8 inch duct where these hot and cold flows mix to cool the hot combustion products prior to their removal from the building.

C. Assembly and Checkout Tests of the System.

C.1 The Combustor Setup. The combustor was assembled on top of a mobile, metal structure. The interchangeability of the various segments in the horizontal section of the setup was checked out. To avoid leaks, ceramic felt gaskets were inserted between the flanges of the heaters in the vertical section, and graphite paste, which also prevents "sticking" of metallic parts, was spread on contact surfaces between the interchangeable sections of the combustor.

C.2 The Air line. The operation of the combustion air supply line was checked out. The tests showed that large pressure drops occurred across the two porous plates located on both sides of the methane injection and mixing section. These porous plates serve as safety devices to prevent flame propagation from the combustor section upstream to the methane injection and mixing section and to prevent methane from diffusing into the electric heater section. The presence of large pressure drops across these plates would have prevented accurate flow rate measurements by the available rotameters and would have prevented the attainment of high velocities in the combustor due to the pressure limitations of the air supply line. The plates were replaced by new, thinner, special stainless steel plates with higher porosity. Tests with the new plates showed that they produced considerably lower pressure drops which resulted in a satisfactory system performance.

C.3 The Methane Line. The methane supply line was tested for leaks and to determine its flow characteristics using air. Leaks were detected and corrected. The flow rate measurement system was tested and found to operate satisfactorily. Upon completion of these tests the methane bottle was connected to the line and the system was rechecked for leaks.

C.4 The Acoustic Power Generation System. The acoustic wave excitation by the system was checked by operating it over prolonged periods of time in the frequency range of 200 to 1500 Hz., which will be used in the planned tests. In addition, the acoustic driving system was operated for short periods (i.e., approximately one minute) in the frequency ranges of 100 - 200 Hz. and 1500 - 2500 Hz. Acoustic pressure transducers located along the combustor section measured dynamic pressures of 130 dB or higher at all of the tested frequencies. It was noted, however, that the activation of the acoustic driving system produced a high level of noise in the laboratory. To reduce the radiated noise level a heavy duty truck muffler was attached to the downstream end of the combustor exhaust section.

C.5 The Air Heaters. The performance of the installed air heaters was tested and it was found that an air temperature of 600°C can be reached at the exit of the heater. However, in order to heat low flow rates of air without burning the heating elements the electric circuitry had to be modified.

C.6 The Computerized Data Acquisition System. A system that consists of an IBM AT computer and a 32 channel LeCroy data logger was purchased at the beginning of 1986 and dedicated for use in this project. The system was tested and it was found that the software for running the data logger was incompatible with the hardware in spite of contrary claims by the LeCroy Company. The LeCroy Company rewrote its software package to match the available hardware. Unfortunately, the process of testing the system and getting the deficiencies corrected lasted nearly 9 months. Although some small changes in the software are yet to be completed, the system is now capable of acquiring and storing data, and transferring the data to the computer for storage and analysis.

C.7 The Data Measurement and Analysis System. All thermocouples, pressure transducers, amplifiers, and chemical analyzers were tested and found to operate satisfactorily. Also, calibration procedures and software for data analysis were developed.

C.8 Ignition of the Catalytic Combustor. Initial attempts to ignite the catalytic combustor with methane concentrations both above and below the lower flammability limit failed even though the mixture temperature at the combustor inlet was above 550°C in all cases. Contacts with investigators at the Alzeta Corporation revealed that the catalyst surfaces need to be heated to a very high temperature (approx. 1375°C) in order to start the catalytic reactions. Consequently, it was decided to preheat the catalyst surfaces with a methane/air flame produced at the beginning of every test by igniting a flammable methane/air mixture upstream of the catalyst section. The resulting flame heats the catalyst surfaces to a very high temperature in a very short time. Subsequently, the methane flow rate is reduced to the desired composition which is below the lower flammability limit. The leaner composition may minimize the occurrence of gas phase reactions and restrict most of the combustion processes to the catalyst surface.

D. Initial Tests of the Catalytic Combustor.

D.1 Objectives. The objectives of the initial tests were to assure the proper operation of the suggested ignition procedure, to check whether all the components of the experimental setup are functioning satisfactorily under actual test conditions and to determine whether the performance of the catalytic combustor changes when switching from pulsating to nonpulsating operating conditions.

D.2 Tests Planning. An ignition section with a .5 inch circular opening in its wall was designed and fabricated. This section was placed upstream of the catalytic combustor section. Ignition of a flammable mixture by inserting a match or a torch through the .5 inch port was planned. Once ignition occurs, the opening is plugged and after several minutes of heating the catalyst surface the methane flow rate is reduced to a level below the lower flammability limit. The lower flammability limit of a methane/air mixture is, approximately, 5% methane by volume. Consequently, a mixture containing 6% methane was chosen for use during the ignition and heatup phases of the experiment. Once the catalyst surface reached the desired temperature the methane concentration is reduced to 4% which confine the reactions to the catalytic combustor section. The initial tests were to be conducted with mixture velocity of 10 m/sec, which is in the middle of the velocity range to be investigated. This velocity corresponds to a flow rate of about 600 liters per minute for an assumed average combustor temperature of 1050°K. Furthermore, an inlet mixture temperature of approximately 500°C, a fixed acoustic wave amplitude (i.e., the acoustic drivers operated at 100 watts), and a fixed location of the catalytic section (i.e., the catalysts are placed at distances between 4 and 9 inches away from the porous plate inside the fuel injection and mixing section which approximates an acoustically hard wall) were selected. The excited wave lengths were estimated to be between 16 inches (at the highest proposed frequency of 1500 Hz.) and 125 inches (at 200 Hz.). Consequently, one would expect that the catalysts are located very close to a pressure anti-node in the low frequency tests and between the pressure node and the pressure anti-node at the high frequency tests. Further estimates show that at a frequency of approximately 1400 Hz. the pressure node is expected to be at the center of the fourth catalyst segment, for a frequency of 1600 Hz. the pressure node is expected to occur near the center of the third catalyst segment and at 1900 Hz. the pressure node is expected to occur near the center of the second catalyst segment.

D.3 Ignition Tests. Attempts to ignite the combustor at a flow rate of 600 liters per minute failed due to extensive outflow of gas through the 1/2 inch ignition opening. This extinguished the matches and a propane pilot flame which were used to ignite the gas mixture. To alleviate this problem, the flow rate was gradually reduced to a flow rate of 170 lit/min at which ignition was possible. In view of this experience, ensuing tests were ignited at lower flow rates.

D.4 Measurements Performed in the Initial tests. Since these tests had the limited objective of determining whether the presence of pulsations affects the performance of a catalytic combustor, the measurements were limited to determination of the flow rates of the reactants, the frequency of the excited pulsations and the time dependencies of the gas temperatures at several locations along the experimental setup. The air and the methane flow rates were determined by using the system described in section C.2 above. The temperatures were recorded by the data acquisition system. The frequency of the excited oscillations was measured by a digital frequency meter which received a signal from the acoustic driving system. The measured frequency was "rechecked" by noting the signals on an oscilloscope which also provided information regarding the magnitude of the amplitude of the excited pulsations. The time dependences of 10 temperatures were recorded during each test. These temperatures were measured by thermocouples and they included the temperatures of the methane and the air as they moved through their respective rotameters, the temperature of the methane/air mixture in the fuel injection and mixing section upstream of the ignition section, the mixture temperature upstream of the of the first catalyst segment, the temperatures downstream of each of the four catalyst segments and the temperatures of the combustion products at two locations downstream of the catalyst section. All the temperatures were measured at the center of the combustor. The data acquisition system was set to sample the temperature data at a rate of 1000 Hz. for a period of approximately one second once every 20 seconds. This setting of the data acquisition system represents a compromise between a need to assure that temperature instabilities do not occur and the need to acquire data over long test durations. In this case observations of the data variations during the one second data acquisition periods, during which the data is recorded every msec., indicated that the measured temperatures varied smoothly with time and temperature instabilities were not observed. Finally, it should be pointed out that although the accuracy of the temperature data acquisition system was found by calibration to be better than ±1°C, the measured data may be affected by radiation and other errors which have not been accounted for.

D.5 Test Results. The first test was initiated by igniting a methane/air mixture containing 6% methane by volume and flowing at a rate of 171 standard lit/min. After about two minutes of operation the mixture flow rate and the methane volume concentration were decreased to 167.2 lit/min and 3.9%, respectively. Observations of the reactions through the ignition port revealed that decreasing the methane concentration resulted in the disappearance of the gas phase flames and the confinement of the reactions to the catalyst surfaces which appeared red hot. At this time the ignition opening was plugged and the behavior of the temperatures measured along the experimental setup with no pulsations present was monitored. With the exception of the thermocouple just downstream of the first catalyst segment, which apparently melted during the ignition phase of the test, all thermocouples appeared to function properly. Observations of the temperatures behavior revealed that the temperatures measured by the thermocouples located between the catalyst segments increased rapidly with time while the increase in the temperatures measured downstream of the catalyst section was more gradual. It was also noted that the temperature downstream of the second catalyst segment reached a level of approximately 1200°C two minutes after the methane concentration was reduced. To avoid additional thermocouple melt downs, it was decided to lower the temperature in the catalyst section by further decreasing the methane concentration. Reducing the methane concentration to 2.9%, the total mixture flow rate to 165.5 lit/min and the mixture inlet temperature to 100°C resulted in a slight drop in the temperature downstream of the second catalyst segment and its stabilization at a level of 1175±5°C. At this point it appeared that the thermocouples would be able to sustain the test temperatures without failure and it was decided to proceed with the conduct of the test. This decision also required switching the data acquisition system from its initial operating mode which allowed continuous monitoring of the measured data to a data storage mode.

After initiating the recording of the temperature data, the catalytic combustor was operated under nonpulsating conditions for 20 minutes. The time averaged temperatures measured along the combustor were 95°C in the injection section, 165°C at the inlet to the first catalyst segment, 1175°C after the second catalyst segment, 1115°C after the third catalyst segment, 875°C after the fourth catalyst segment, and 690°C and 470°C in the center of the combustor at distances of 16.5 and 39 inches downstream of the catalyst section, respectively. This temperature profile is presented in Figure 2 where the specified distances are measured from the porous plate upstream of the ignition section. After 20 minutes of steady state operation, the combustor was operated under pulsating conditions. Specifically, pulsations with frequencies of 230 Hz., 458 Hz., 1606 Hz., 803 Hz. and 321 Hz. were excited sequentially in the combustor. Operation at a specific frequency normally lasted between two to four minutes and it was followed by a period of steady state operation which lasted up to 5 minutes. During the test the temperature downstream of the second catalyst segment was monitored on the computer screen, and decisions regarding the duration of each test condition were made by evaluating the time needed for this temperature to stabilize. Time histories of the temperatures measured under pulsating conditions are presented in Figures 3 through 7. The plots designated by Nos.7 8 and 9 describe temperatures measured just downstream of the second, third and fourth catalyst segments, respectively. The two vertical lines denoted by "acous.pwr" represent the instants at which the acoustic driving system was turned on and off. Thus, each figure describes the behavior of the temperatures at various locations along the catalyst section in the presence and absence of an acoustic field having a specific frequency. The time is measured relative to an arbitrary instant, usually near the initiation of pulsations, which was chosen as zero time. The total duration of this test was 70 minutes.

A second test was performed after replacing the burned thermocouple with a new one. The objectives of the second test were to check whether the meltdown of the thermocouple can be avoided, whether the results attained in the first test are reproducible and to check the effect of pulsations over a broader frequency range. As in the first test, the ignition of a mixture of 6% methane by volume and a flow rate of 171 lit/min was initiated by a propane torch. The ignition opening was immediately plugged and after approximately two minutes the methane concentration and mixture flow rate were reduced to 2.9% and 165.5 lit/min, respectively. The air heaters were turned on only after the concentration of methane was reduced. The system was operated under nonpulsating conditions for about 7 minutes, although the temperatures had reached nearly constant values after about two minutes, see Figure 8. Following the steady phase, the combustor was operated while subjected to pulsations with frequencies of 150, 200, 300, 430, 575, 720, 940, 1150, 1500, 2000, and 3000 Hertz, in the indicated order. The time histories of the temperatures measured in this test are presented in Figures 9 through 19. It should be pointed out that in these tests the thermocouple downstream of the first catalyst segment was not damaged and its measured temperature is designated by No. 6. The duration of this test was 55 minutes.

D.6 Discussion of Results. Analysis of the temperature profiles presented in Figures 2 and 8, as well as the plots of the time histories show that the temperatures drop significantly downstream of the second catalyst segment which indicates that only the upstream sections of the catalyst were "active" in these tests. Although concentrations of the products were not measured, it is assumed that all the methane reacted while passing over the first two catalyst segments and that the catalytic combustor is capable of operating at much higher flow rates as planned.

Very high temperature rises (150°C or more) were observed down stream of the second catalyst segment (see Figures 3, 4, 9, and 17) when pulsations were introduced. This indicates that pulsations have significant effect on the performance of the catalytic combustor. The temperature rise is much lower in some cases (i.e., see Figures 5, 6, 12, 14, 15, and 18) and negligible in others (i.e., see Figures 7, and 19). This suggests that the effect of pulsations on the catalytic combustion is frequency dependent. A significant difference exists between the temperature profiles measured under nonpulsating conditions in the first test (i.e., see Figure 2) as compared to those measured in the second one (see Figure 8). Although different ignition procedures were used in these tests, the steady state operating conditions were the same in both tests, and this may indicate that the previous history of the operation of the combustor is affecting its performance (i.e, hysteresis effects). The fact that after turning the pulsations off the temperatures do not return to the same values measured prior to the introduction of pulsations, as seen in most of the figures, also support the view that hysteresis effects exist. However, the observed behavior may be also caused be other factors, such as the need for a much longer time to reach steady state conditions, as indicated in the literature [6].

It should be noted that at the higher frequencies (above 1600 Hz.) the effect of the pulsations was expected to be significant due to the existence of a pressure node in the catalyst section. Although a high temperature rise was detected at 1500 Hz. (see Figure 17), a more moderate rise was measured for 1606 Hz. (see Figure 5), a slight one at 2000 Hz. and no temperature rise was observed when the catalytic combustor was subjected to pulsations of 3000 Hz. Other results, such as the temperature drop upon the introduction of pulsations and/or the temperature rise when the pulsations were turned off (see Figures 9, 10, 11, and 16) are also very intriguing.

In summary, several trends emerge from analyzing the results of the preliminary tests:

(1) Under certain operating conditions the performance of a catalytic combustor can be affected by the presence of an acoustic field.

(2) The response of the catalytic combustor performance to pulsations depends upon the frequency of the excited waves.

(3) The large temperature variations observed in the catalyst section suggests that operating catalytic combustors under pulsating conditions at certain frequencies can result in significant improvements of their performance.

WORK PLANNED FOR THE COMING YEAR

During the next contract year, the following efforts will be emphasized:

A - Development of an Electric Arc Ignition Technique.

The tests conducted with the pilot flame ignition system revealed that it is inadequate at flow rates higher than those utilized in the tests reported herein. Consequently, a new ignition system will have to be developed. At present, an ignition system utilizing a 10000 Volt electric arc between a stainless steel electrode and a grounded stainless steel flame holder is being developed. Upon completion of its assembly, check out tests aimed at determining whether this ignition system is capable of igniting the test mixtures and initiating catalytic combustion over the entire range of flow rates, will be conducted. The flame holder was designed to be replaceable so that different flame holders can be utilized for different reactants flow rates in use, if such versatility will be needed.

B - Development of Software for Data Reduction.

The changes which are needed in the software controlling the LeCroy data logger will be incorporated into the system, and a menu driven master program capable of handling data reduction will be developed.

C - Determination of the Performance of the Catalytic Combustor Under Nonpulsating Conditions.

The performance of the catalytic combustor will be investigated over the entire range of planned mixture flow rates without exciting pulsations. Temperatures and acoustic pressures will be measured to determine the time needed to reach steady state operating conditions, the acoustic noise generated within the setup by the combustion and flow processes and the characteristics of the nonpulsating catalytic combustion. In addition, the chemical composition of the combustion products will be determined and used to calculate the combustion efficiency and pollutant formation of the catalytic combustor.

D - Determination of the Performance of the Catalytic Combustor Under Pulsating Conditions.

Pulsating catalytic combustion tests will be conducted at one of the previously investigated steady state test conditions which produced a combustion efficiency of around 70%. In a typical test, the system will be ignited and operated initially under nonpulsating conditions until a steady state operating condition has been reached. Next, an acoustic standing waves of specified amplitude and frequency will be excited and the performance of the catalytic combustor will be monitored. During these tests the acoustic pressures at different combustor locations will be measured to determine the characteristics of the excited acoustic standing wave and locate the catalyst section at a pressure node. Both the temperature distribution along the combustor and the chemical composition of combustion products will be measured to determine the effect of pulsations on the performance of the catalytic combustor. Tests will be conducted at different frequencies in the range of 200 to 1500 Hertz. In addition the effect of amplitude variations upon the combustor performance will be determined by conducting tests with different wave amplitudes at specific frequencies.

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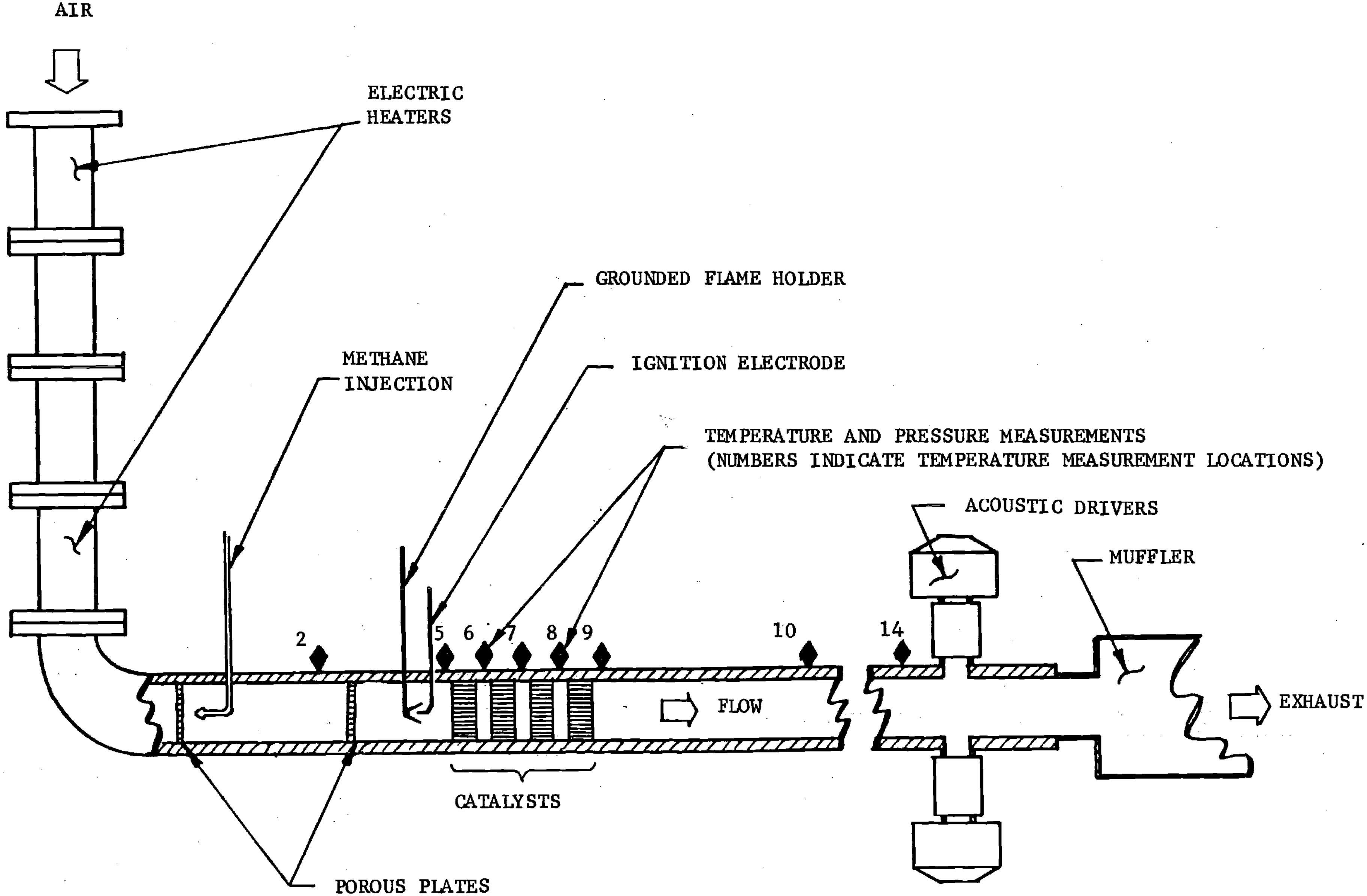

Figure 1. A Schematic of the Developed Pulse Catalytic Combustor Experimental Setup.

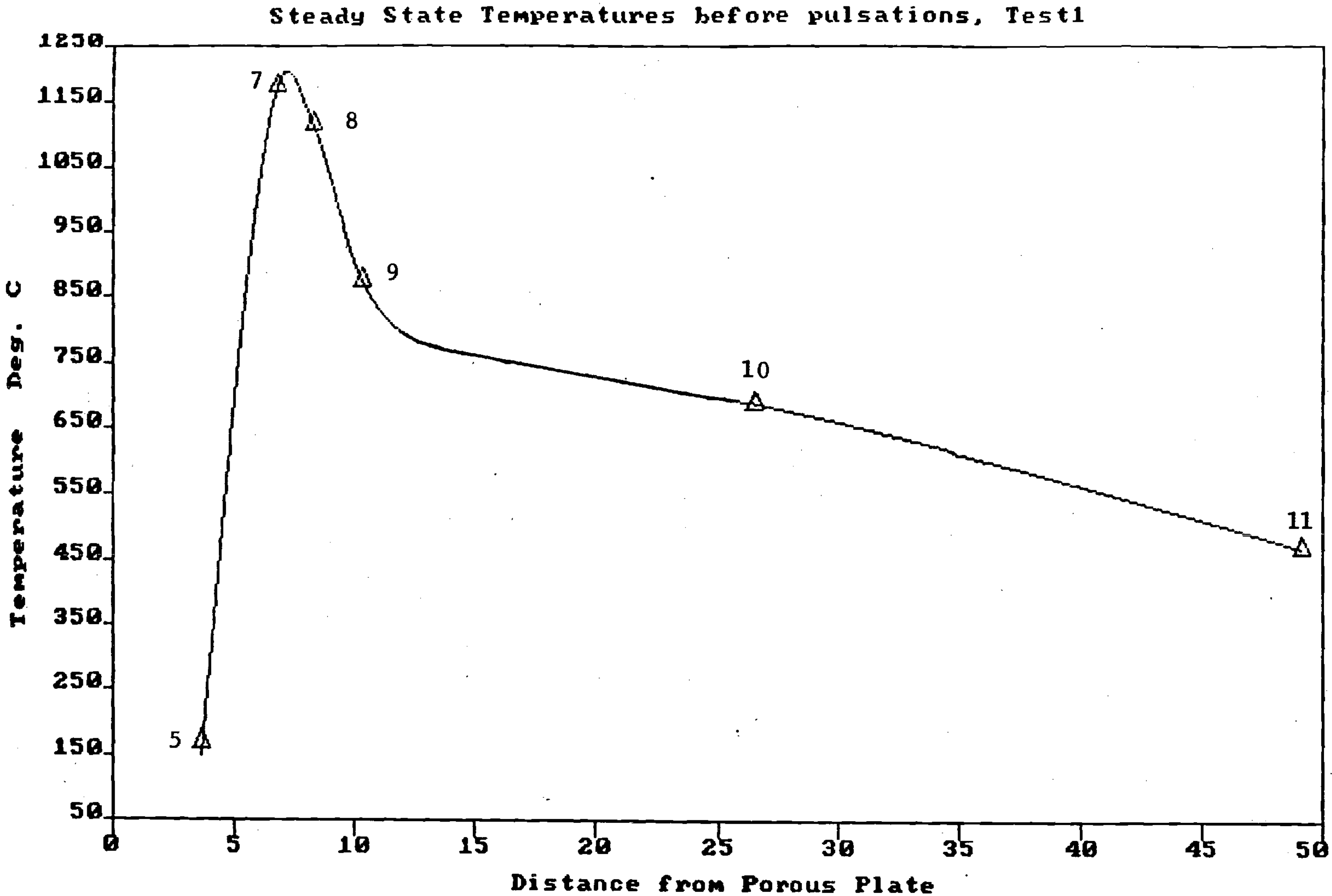

Figure 2. Steady State Temperature Profile before Exciting Pulsations in Test Sequence No. 1. Numbers indicate the Thermocouples Locations, see Fig. 1.

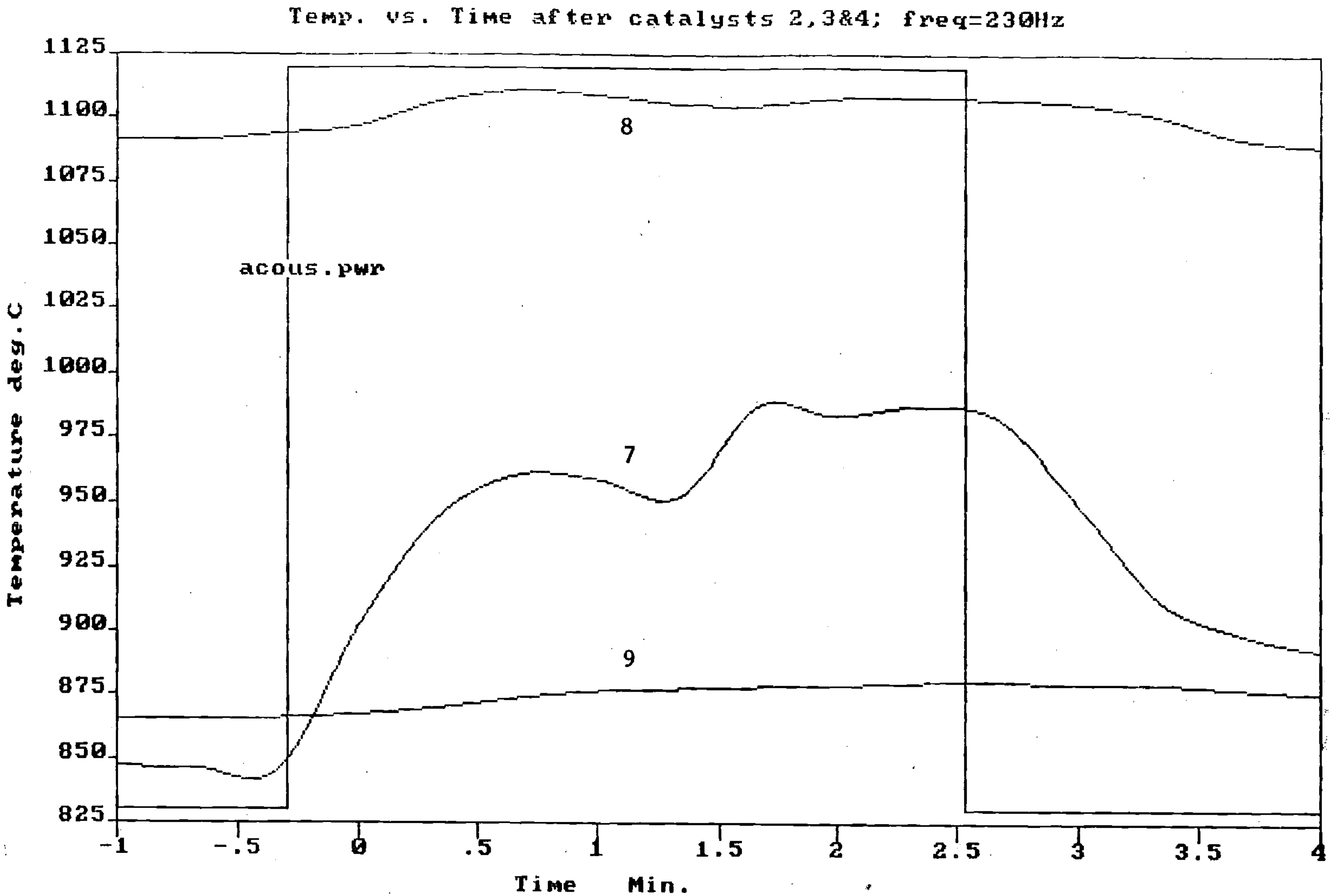

Figure 3. Time Histories of Catalytic Combustor Temperatures Before, During and After the Excitation of a 230 Hz. Acoustic Field During Test Sequence No. 1.

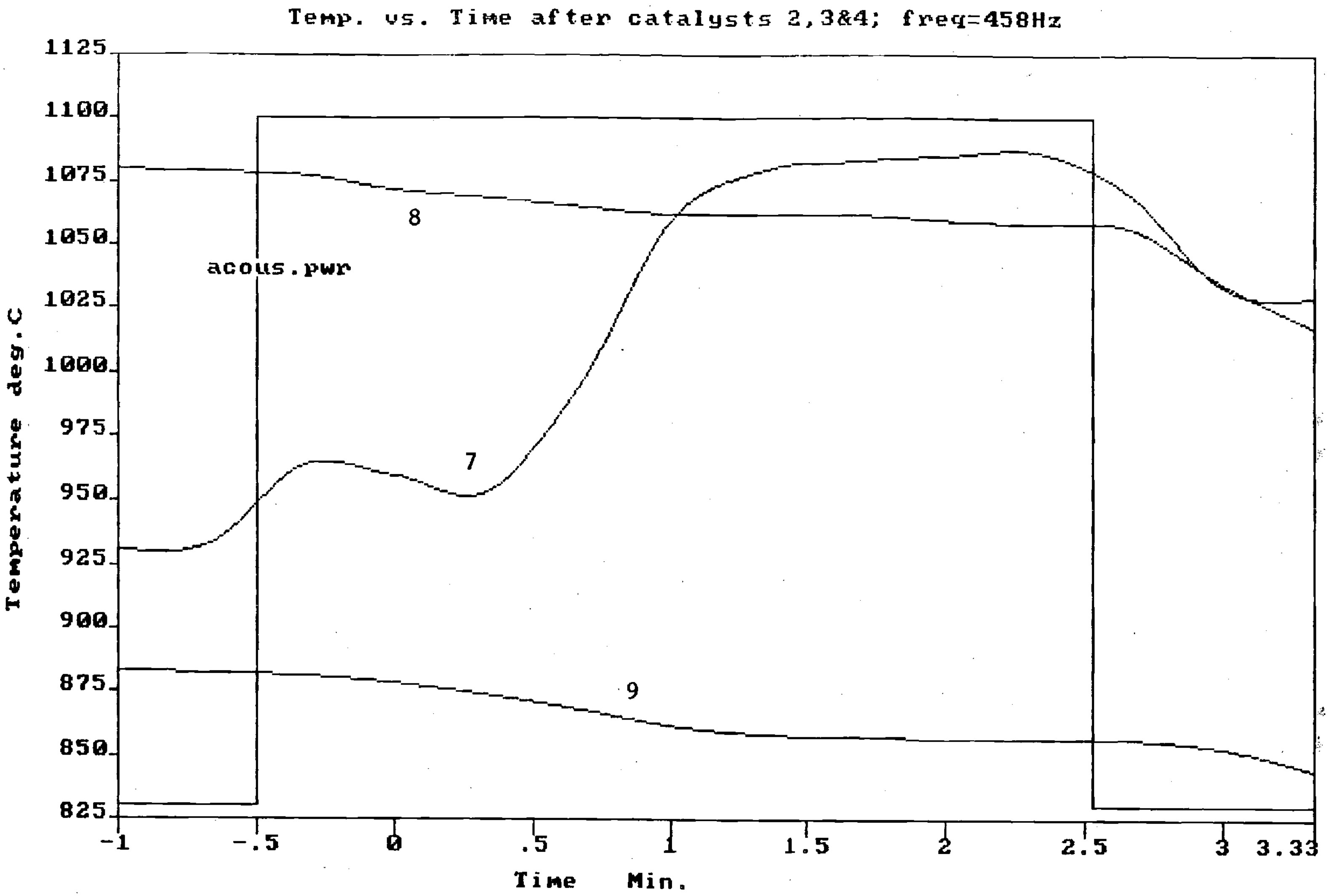

Figure 4. Time Histories of Catalytic Combustor Temperatures Before, During and After the Excitation of a 458 Hz. Acoustic Field During Test Sequence No. 1.

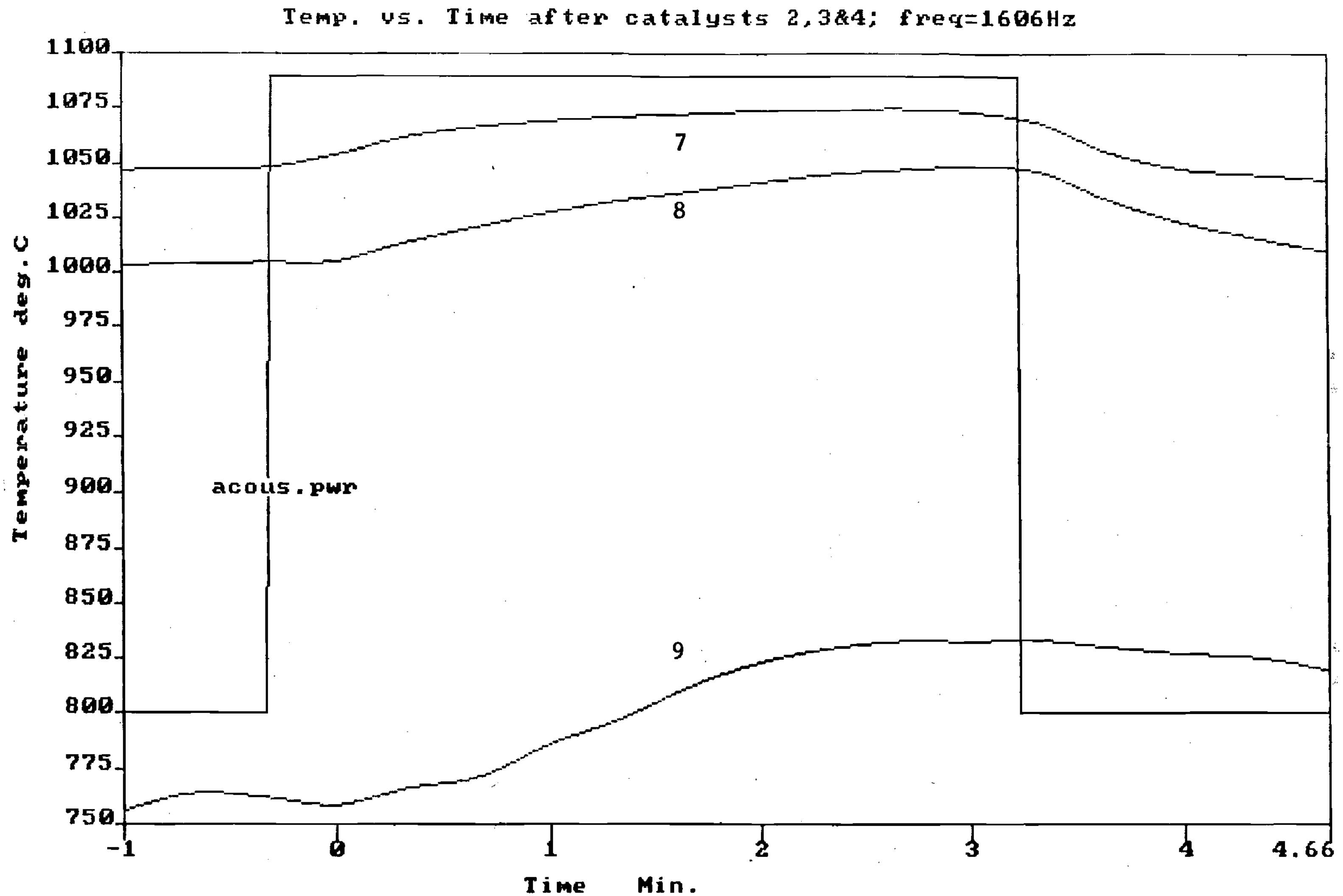

Figure 5. Time Histories of Catalytic Combustor Temperatures Before, During and After the Excitation of a 1606 Hz. Acoustic Field During Test Sequence No. 1.

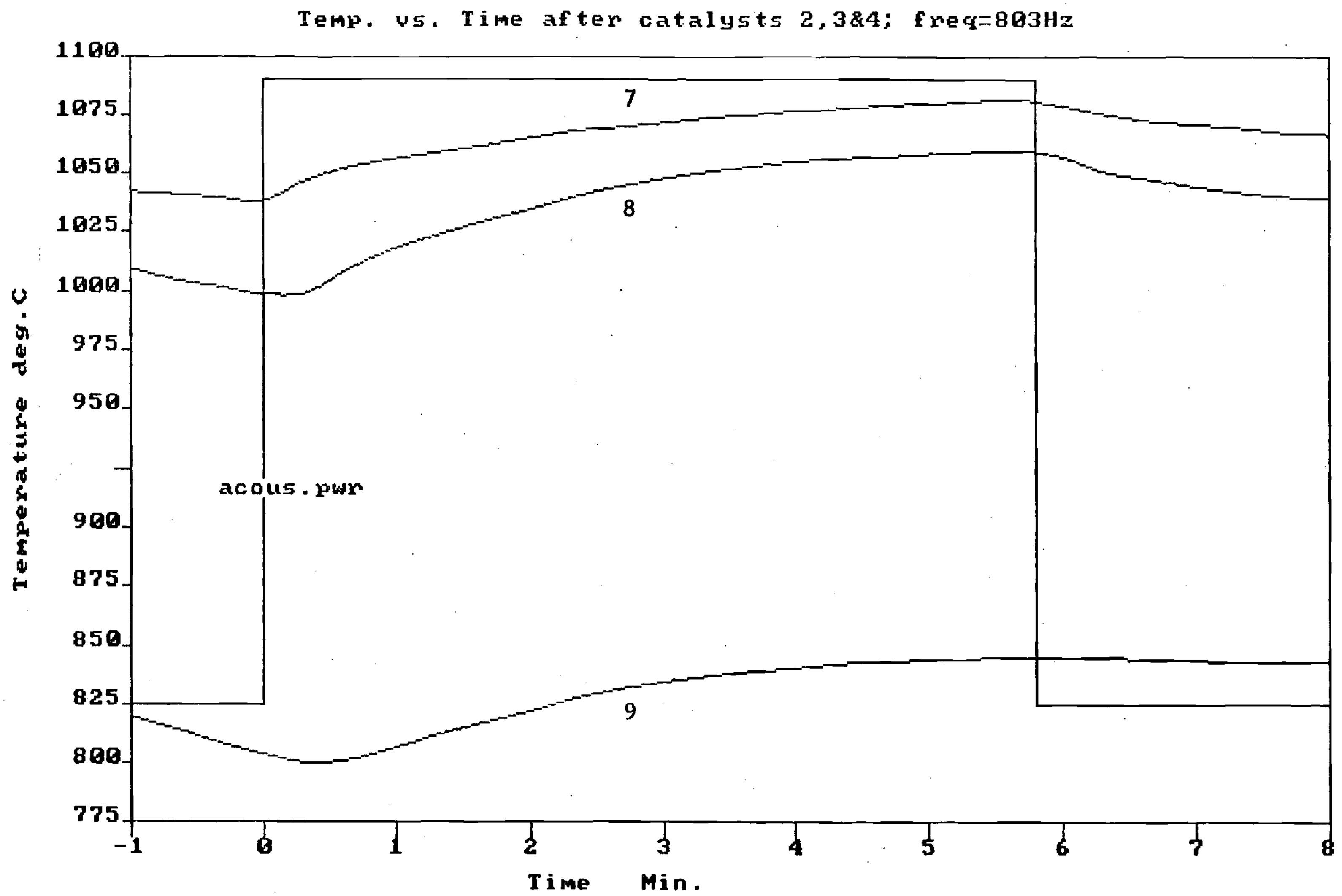

Figure 6. Time Histories of Catalytic Combustor Temperatures Before, During and After the Excitation of a 803 Hz. Acoustic Field During Test Sequence No. 1.

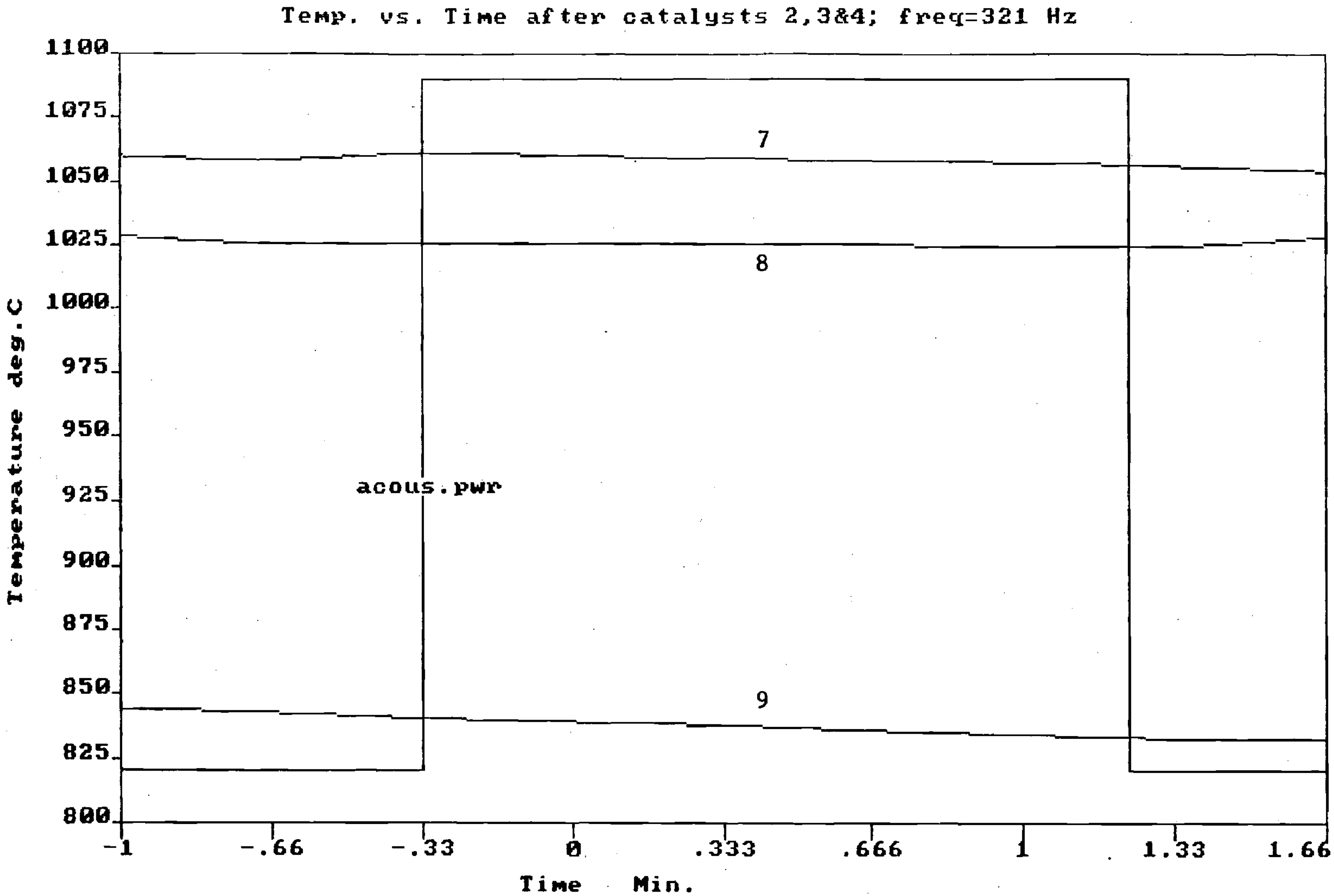

Figure 7. Time Histories of Catalytic Combustor Temperatures Before, During and After the Excitation of a 321 Hz. Acoustic Field During Test Sequence No. 1.

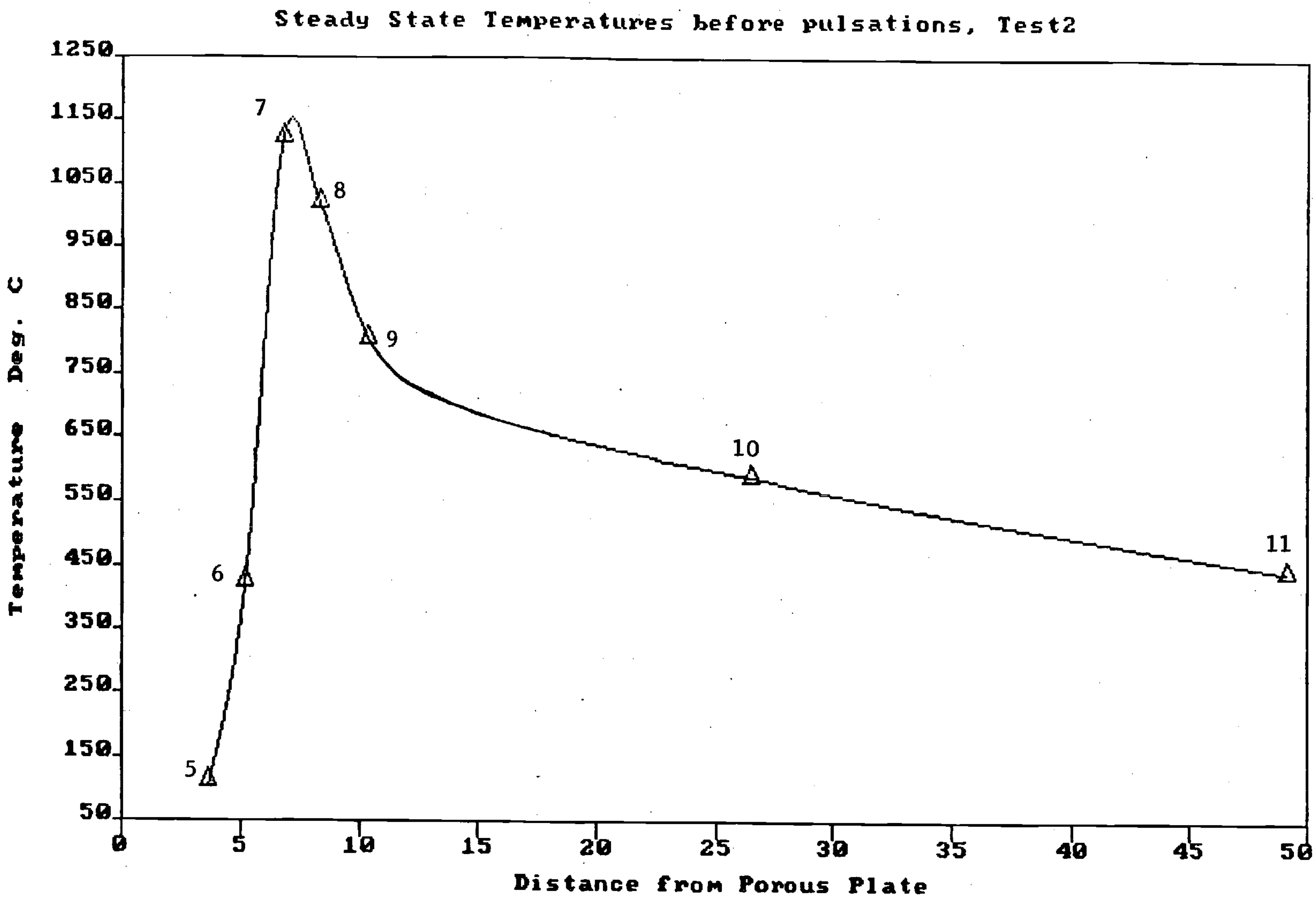

Figure 8. Steady State Temperature Profile before Exciting Pulsations in Test Sequence No. 2. Numbers indicate the Thermocouples Locations, see Fig. 1.

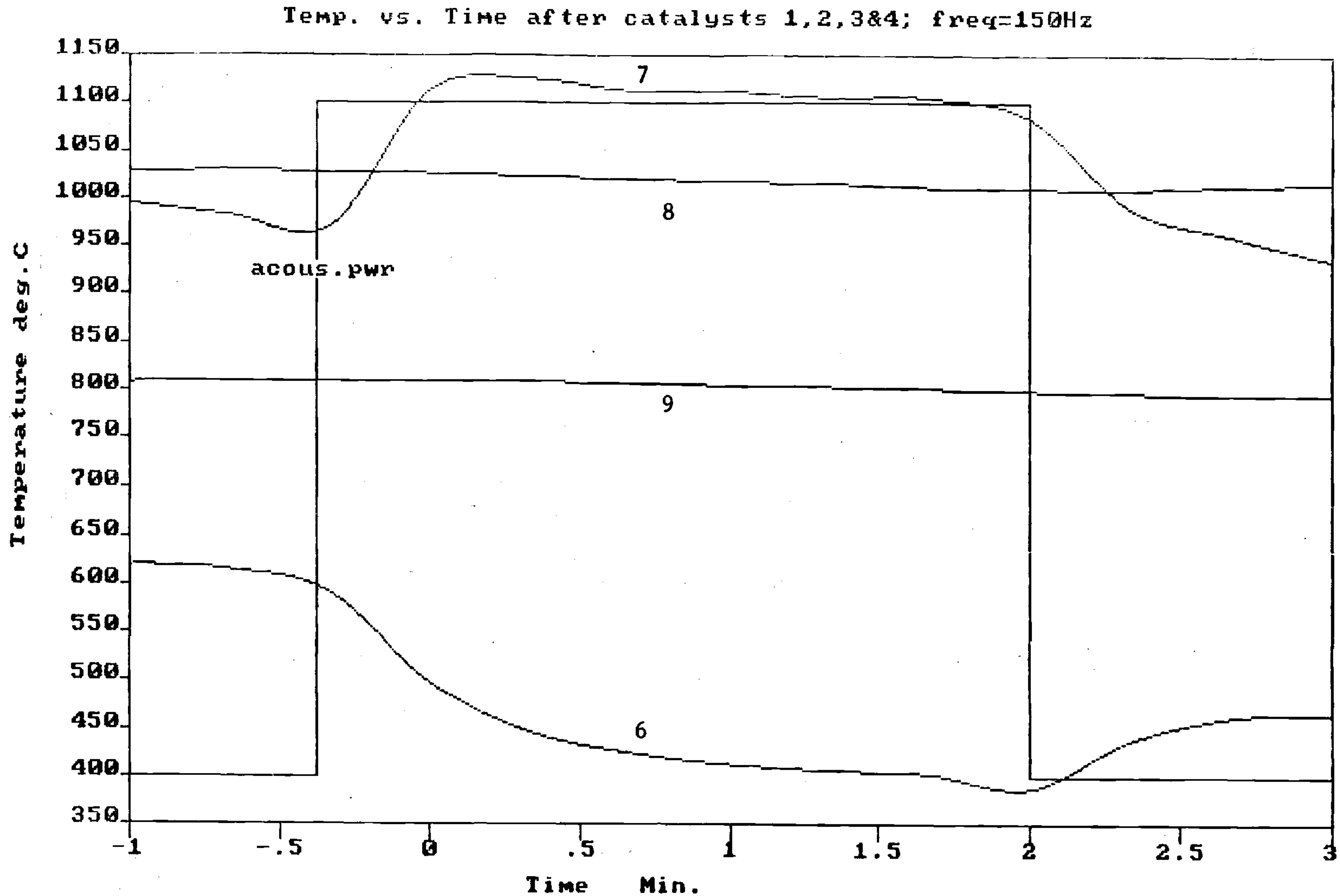

Figure 9. Time Histories of Catalytic Combustor Temperatures Before, During and After the Excitation of a 150 Hz. Acoustic Field During Test Sequence No. 2.

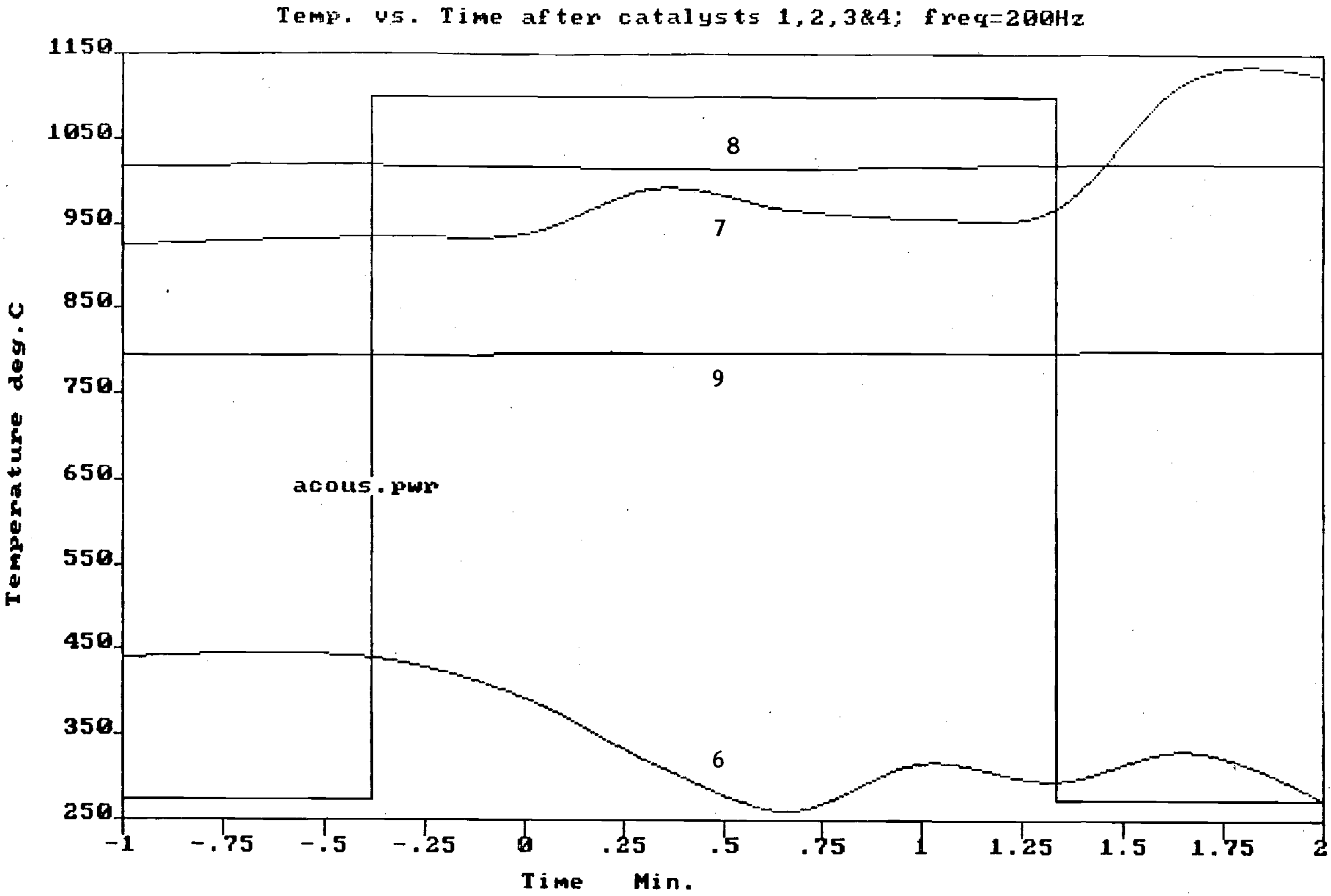

Figure 10. Time Histories of Catalytic Combustor Temperatures Before, During and After the Excitation of a 200 Hz. Acoustic Field During Test Sequence No. 2.

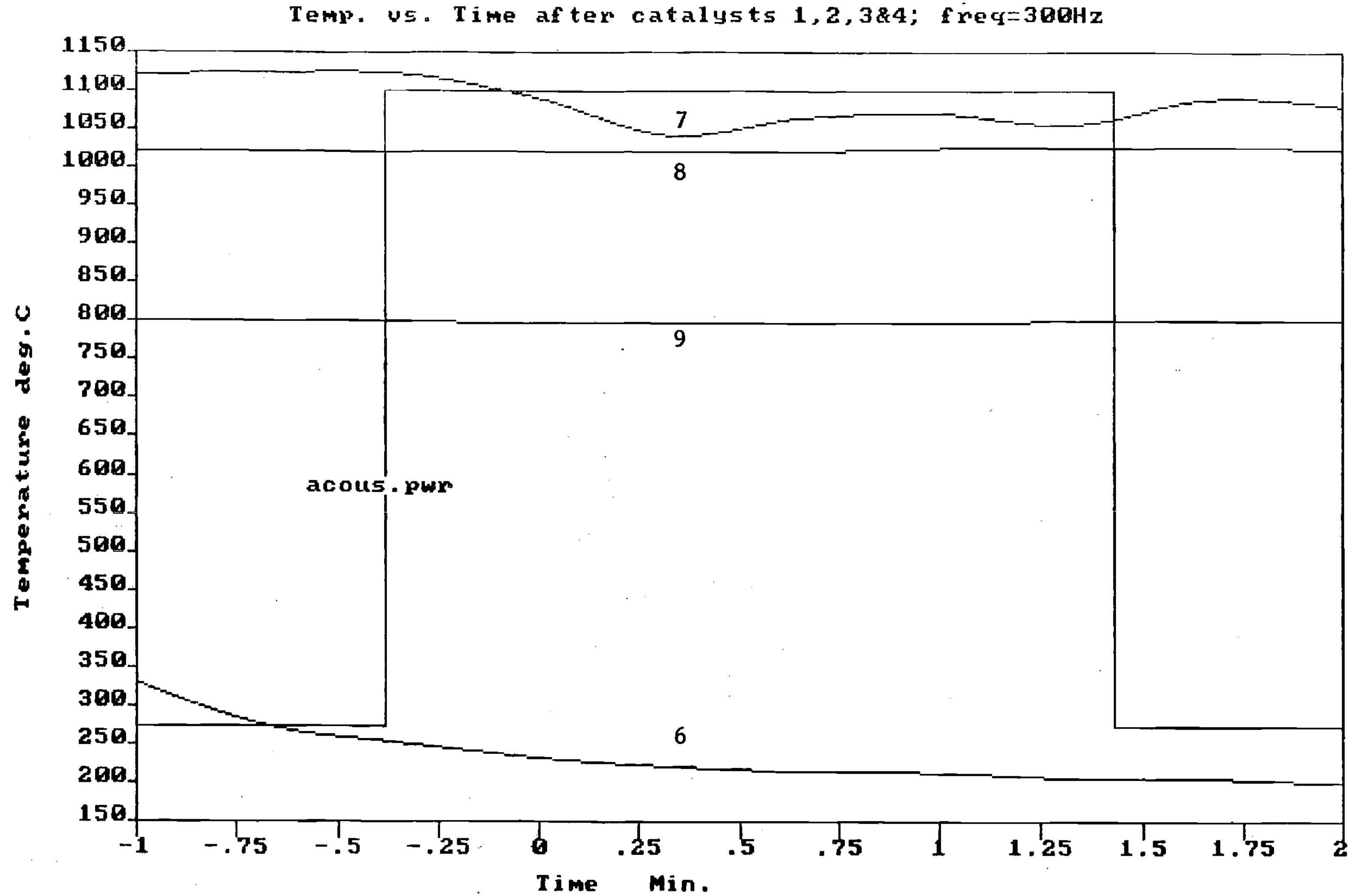

Figure 11. Time Histories of Catalytic Combustor Temperatures Before, During and After the Excitation of a 300 Hz. Acoustic Field During Test Sequence No. 2

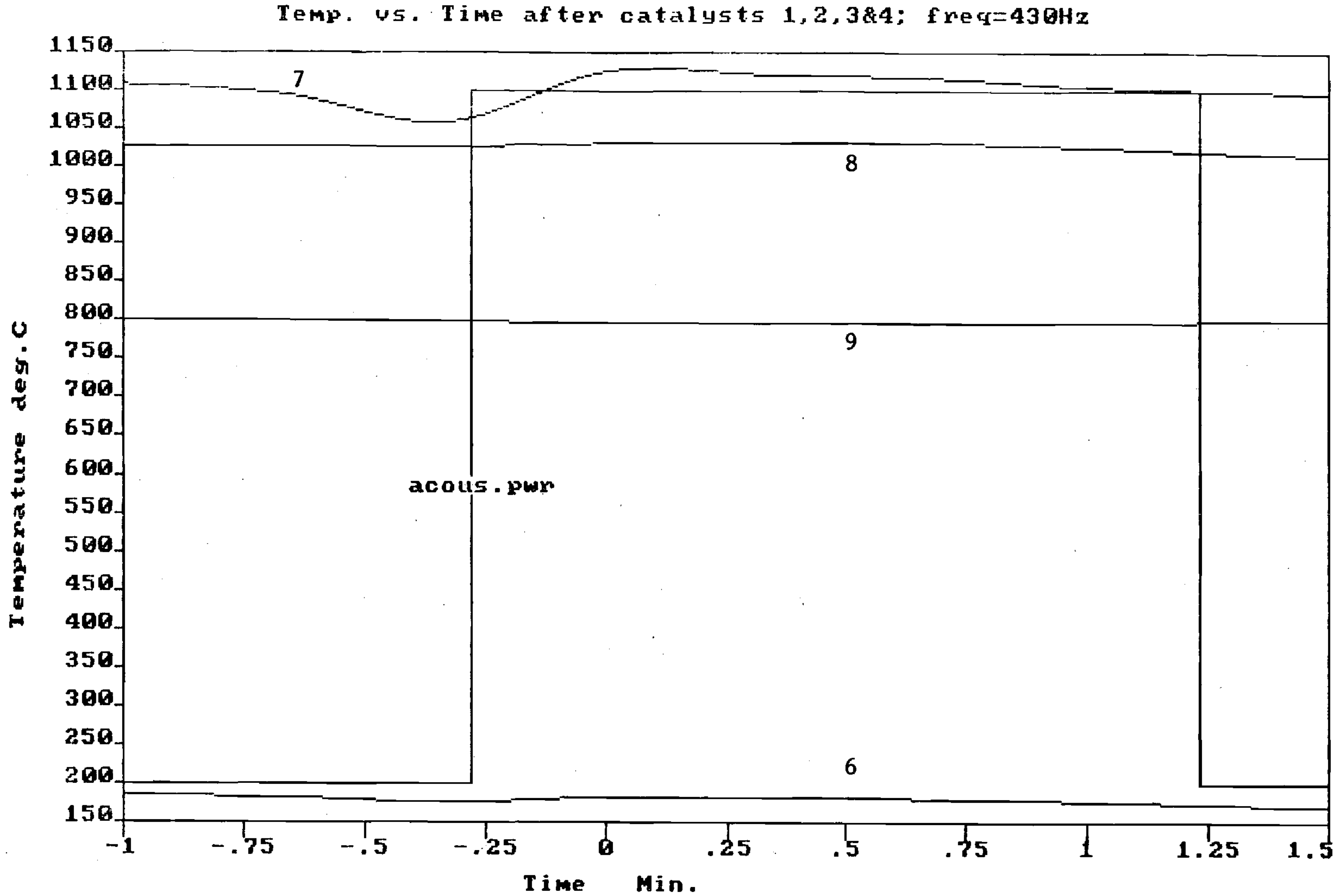

Figure 12. Time Histories of Catalytic Combustor Temperatures Before, During and After the Excitation of a 430 Hz. Acoustic Field During Test Sequence No. 2.

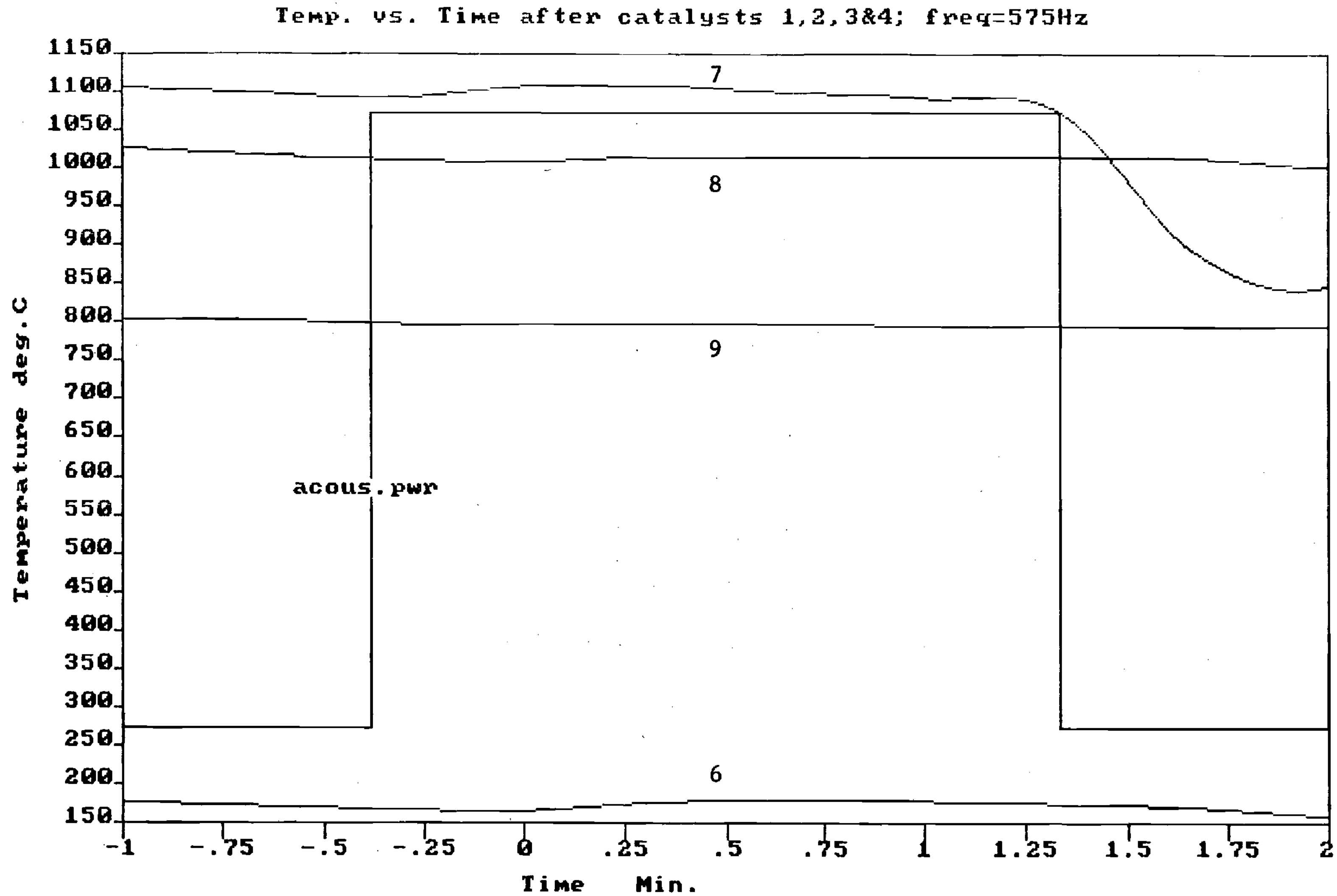

Figure 13. Time Histories of Catalytic Combustor Temperatures Before, During and After the Excitation of a 575 Hz. Acoustic Field During Test Sequence No. 2.

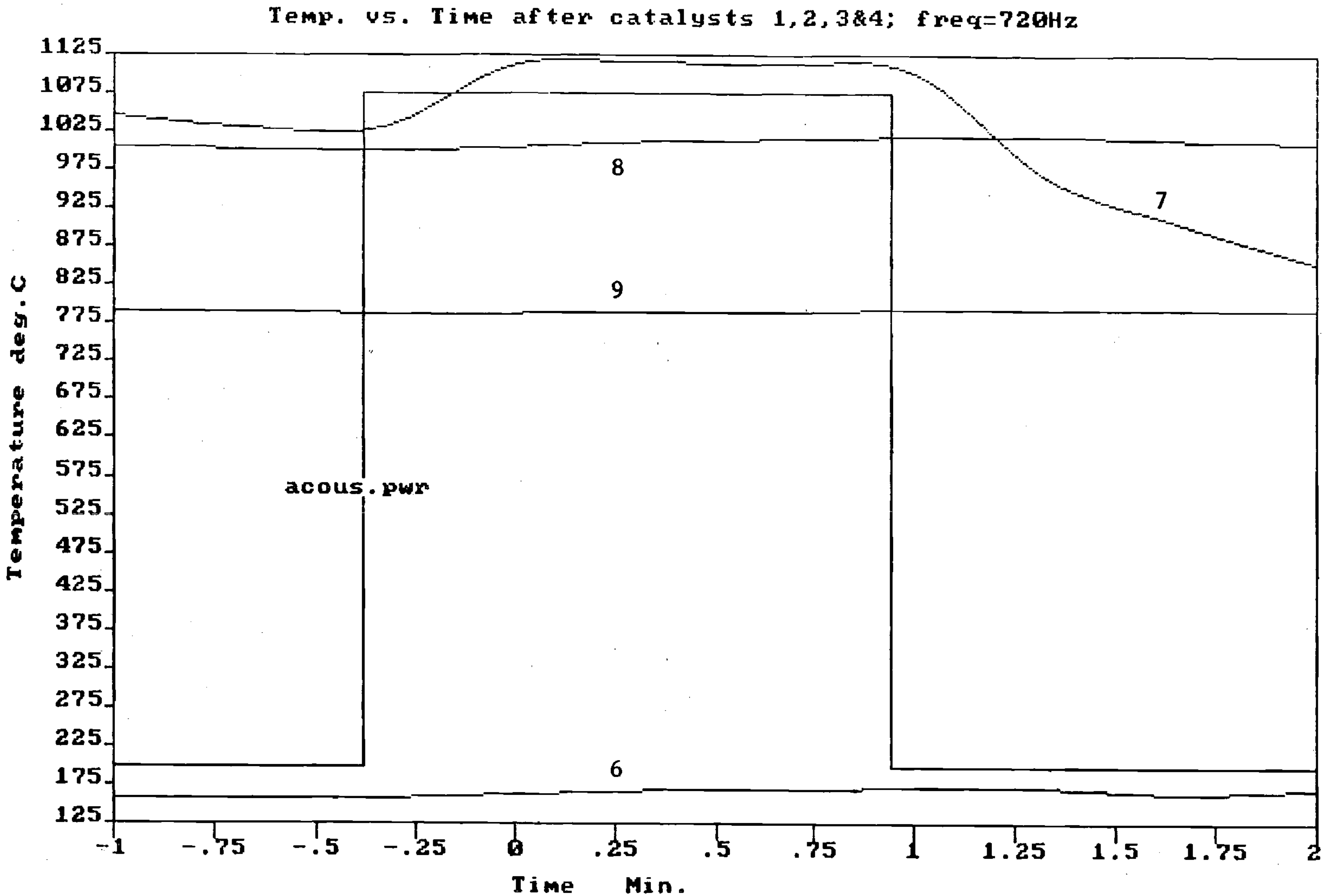

Figure 14. Time Histories of Catalytic Combustor Temperatures Before, During and After the Excitation of a 720 Hz. Acoustic Field During Test Sequence No. 2.

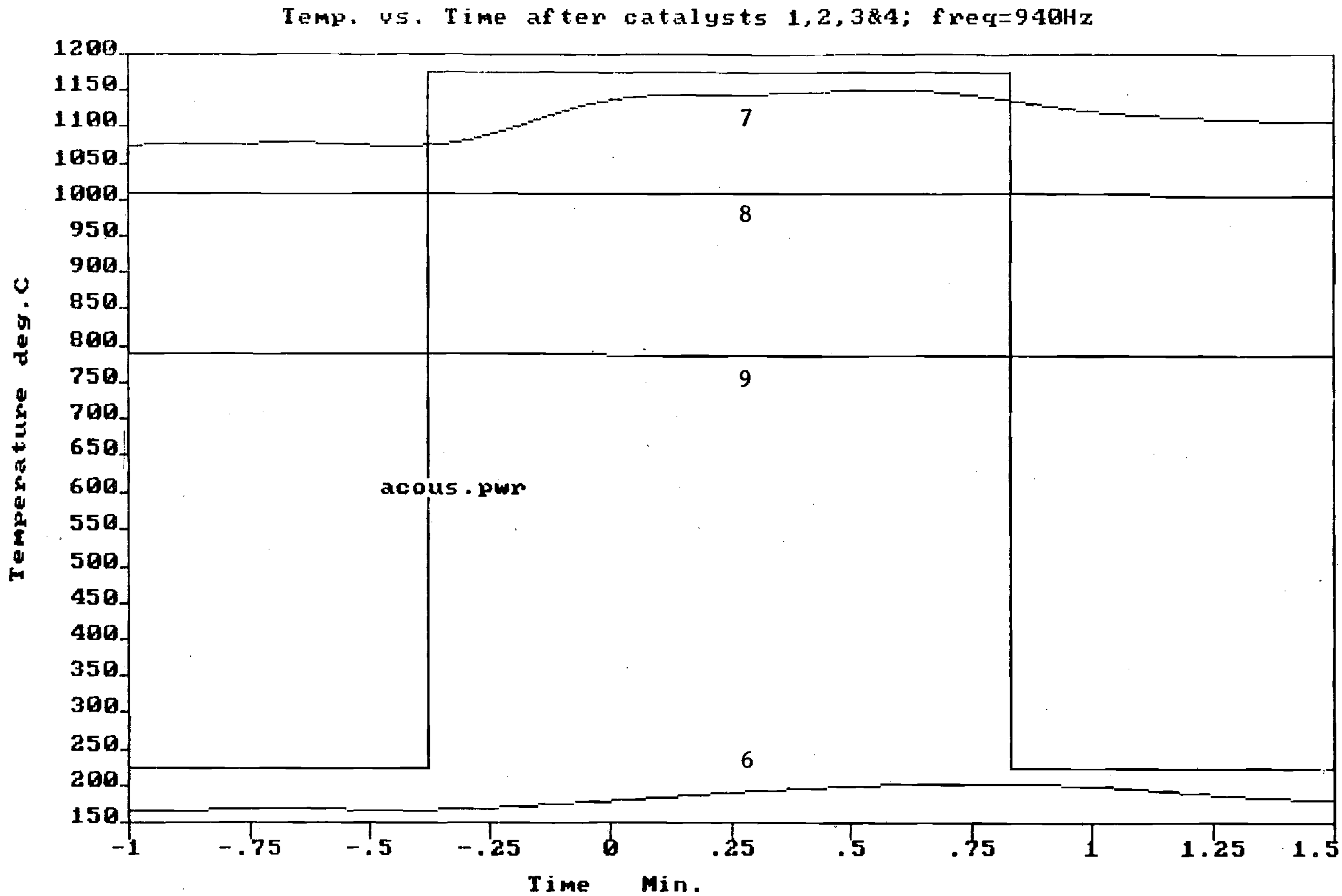

Figure 15. Time Histories of Catalytic Combustor Temperatures Before, During and After the Excitation of a 940 Hz. Acoustic Field During Test Sequence No. 2.

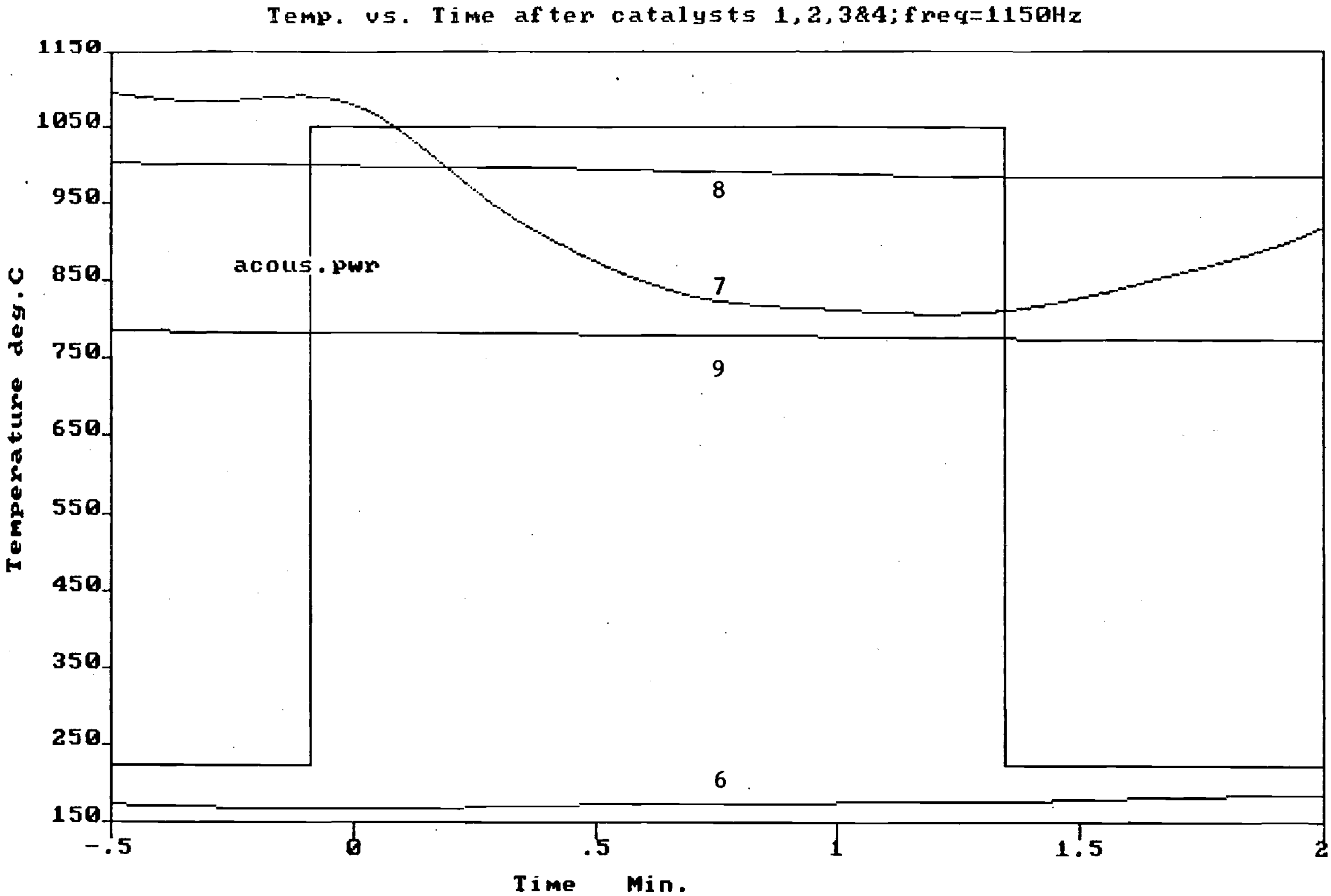

Figure 16. Time Histories of Catalytic Combustor Temperatures Before, During and After the Excitation of a 1150 Hz. Acoustic Field During Test Sequence No. 2.

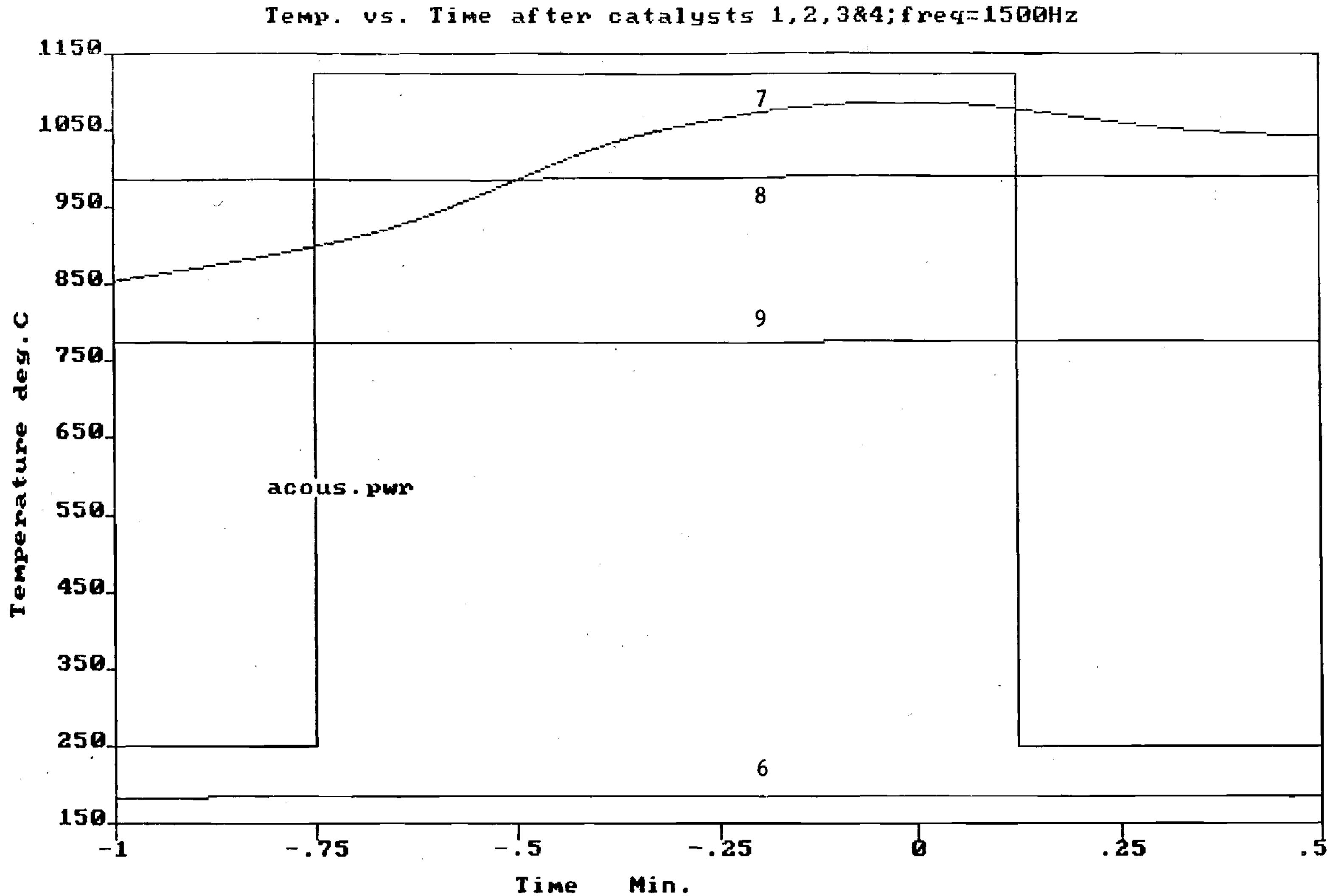

Figure 17. Time Histories of Catalytic Combustor Temperatures Before, During and After the Excitation of a 1500 Hz. Acoustic Field During Test Sequence No. 2.

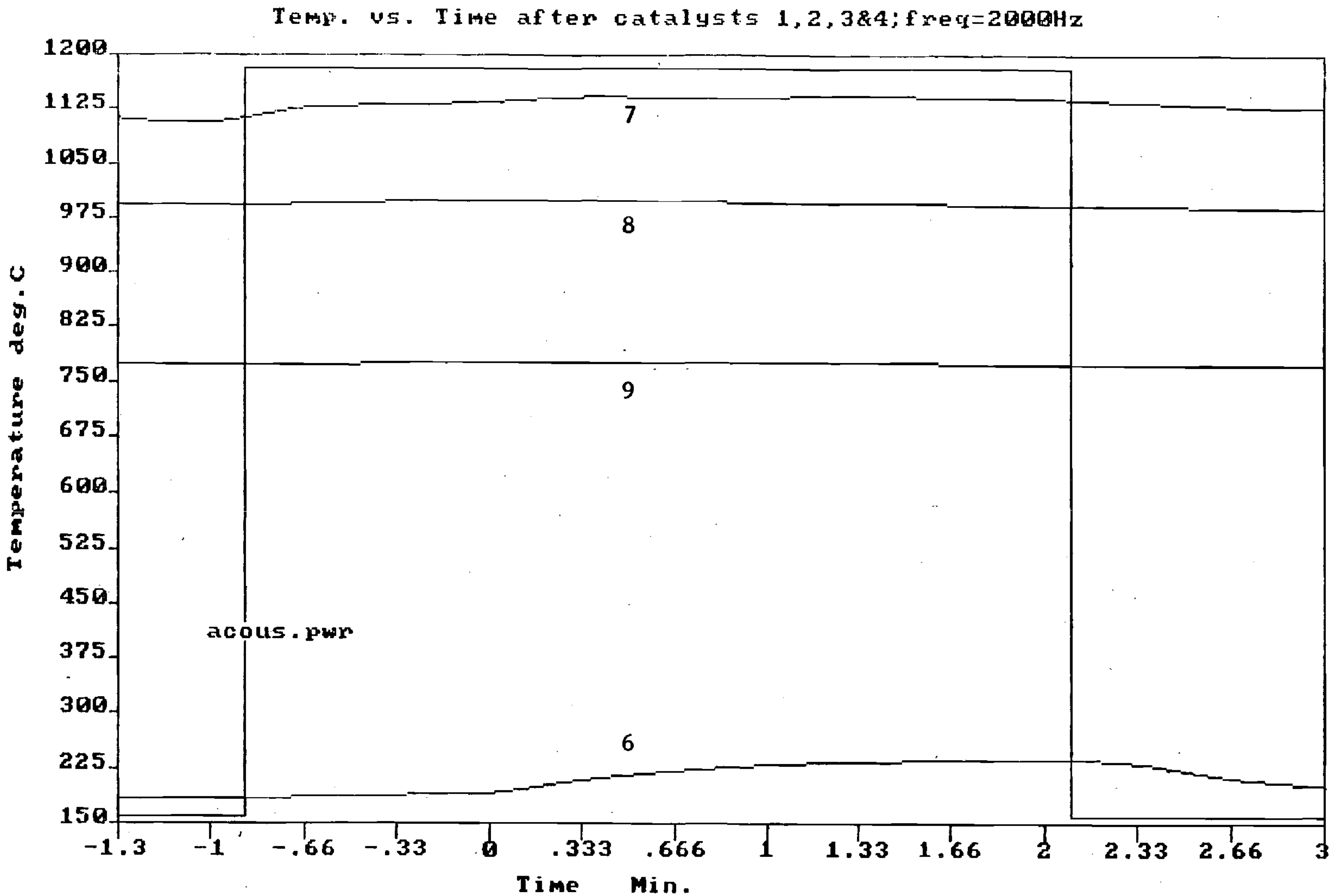

Figure 18. Time Histories of Catalytic Combustor Temperatures Before, During and After the Excitation of a 2000 Hz. Acoustic Field During Test Sequence No. 2.

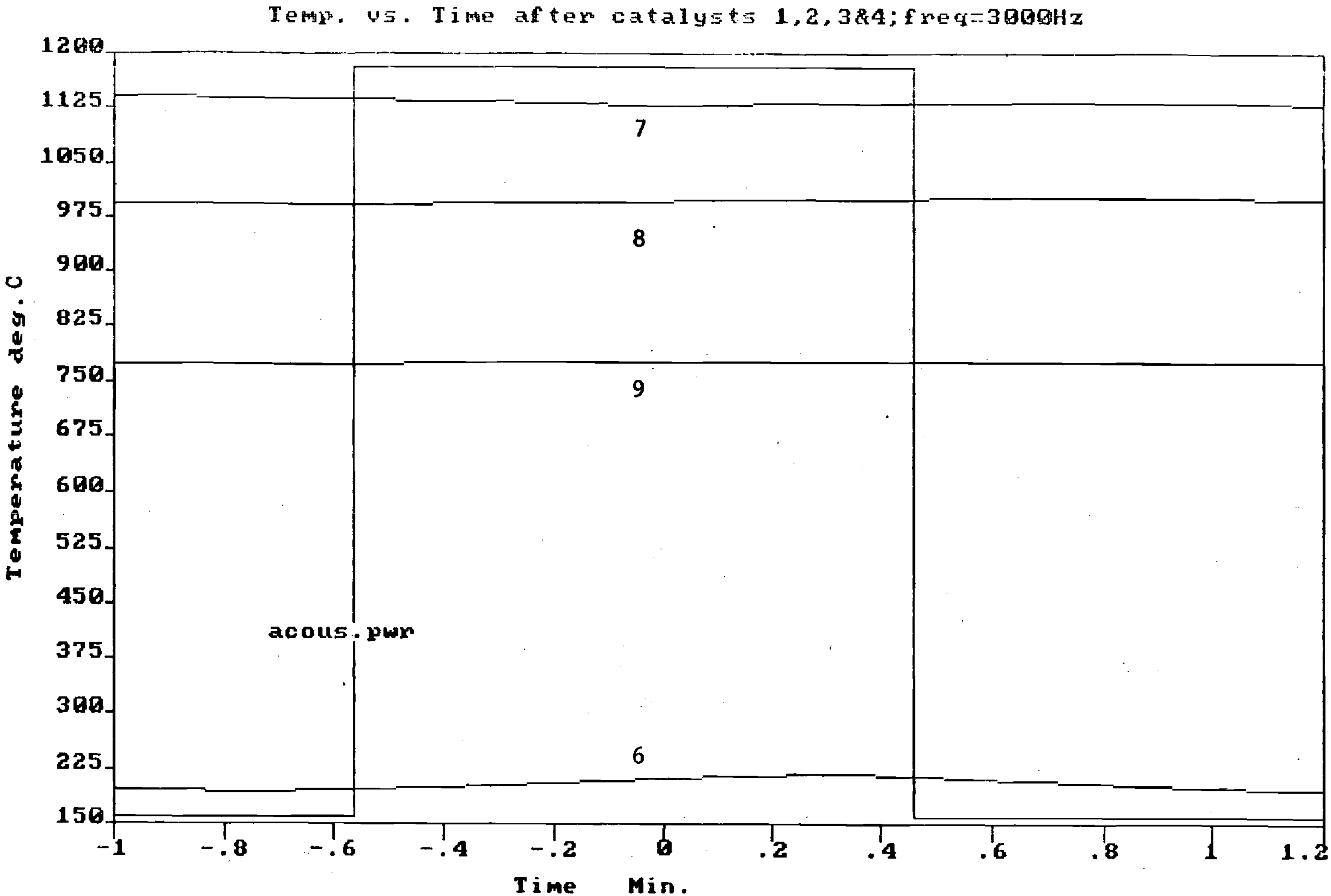

Figure 19. Time Histories of Catalytic Combustor Temperatures Before, During and After the Excitation of a 3000 Hz. Acoustic Field During Test Sequence No. 2.